Results of Ground-Water Tracer Tests Using Tritiated Water at Oak Ridge National Laboratory, Tennessee

By D.A. WEBSTER

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
810 Broadway, Suite 500
Nashville, Tennessee 37203

Copies of this report may be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
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TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	2.54 x 10	millimeters
inch (in.)	2.540	centimeters
foot (ft)	0.3048	meter
foot per hundred feet	0.3048	meter per hundred meters
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.6093	kilometer
curie (Ci)	2.22×10^{12}	disintegrations per minute
curie (Ci)	3.70×10^{10}	becquerels
disintegrations per minute (dpm)	0.4505	picocuries
disintegrations per minute per milliliter (dpm/mL)	4.505×10^{2}	picocuries per liter
disintegrations per minute per milliliter (dpm/mL)	1.667 x 10	becquerels per liter

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Results of Ground-Water Tracer Tests Using Tritiated Water at Oak Ridge National Laboratory, Tennessee

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ABSTRACT

Ground-water tracer tests were conducted at two sites in the radioactive-waste disposal area of Oak Ridge National Laboratory from 1977 to 1982. The purpose of the tests was to determine if the regolith beds had weathered sufficiently to permit the substantial flow of water across them. Regolith of the sites has developed on the Pumpkin Valley Shale and the Nolichucky Shale of the Conasauga Group, both of Cambrian age. About 50 curies of tritium dissolved in water were used as the tracer at one site, and about 100 curies at the other. Distances from the injection wells to a semi-circle of observation wells were 12 and 30 feet, respectively. Results demonstrated that ground water is able to flow through joints in the weathered bedding and that the direction of the water-table gradient is the primary factor governing flow direction. Nevertheless, the substantial lateral spread of the plume as it developed showed that bedding-plane openings, important in controlling flow in the deeper rock, can still exert a significant secondary influence on flow direction in the weathered rock.

About 3,500 water samples from the injection and observation wells were analyzed for tritium during the test period. Concentrations detected spanned 11 orders of magnitude. Measurable concentrations were still present in the two injection wells and most observation wells 5 years after the tracer was introduced.

Matrix diffusion may have played a significant role in these tests. The process would account for the sustained concentrations of tritium at many of the observation wells, the long-term residual concentrations at the injection and observation wells, and the apparent slow movement of the centers of mass across the two well fields. The process also would have implications regarding aquifer remediation. Other tracer tests have been conducted in the regolith of the Conasauga Group. Results differ from the results described in this report.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) in eastern Tennessee (fig. 1) is one of several research facilities administered by the U.S. Department of Energy. As a by-product of research activities that span five decades, substantial quantities of radioactively contaminated wastes have been produced at this facility and have been disposed of by consignment to the shallow earth. From 1951 until 1986, solid wastes were buried in shallow, unlined trenches in three burial grounds in the Melton Valley part of the Laboratory, and from 1951 through 1965, liquid wastes that could not be readily decontaminated were chemically treated and discharged to shallow open pits, also in Melton Valley, from which the liquids percolated. Water samples from wells and local drainages indicated that the transport of most contaminants in the liquids was limited in distance by sorption and ion exchange with the geologic media through which the liquids passed.

Several studies that relate to the long-term safety of the ground disposal of wastes, particularly of the liquid wastes, were conducted during the 1950's and 1960's. The hydrogeologic studies concluded that

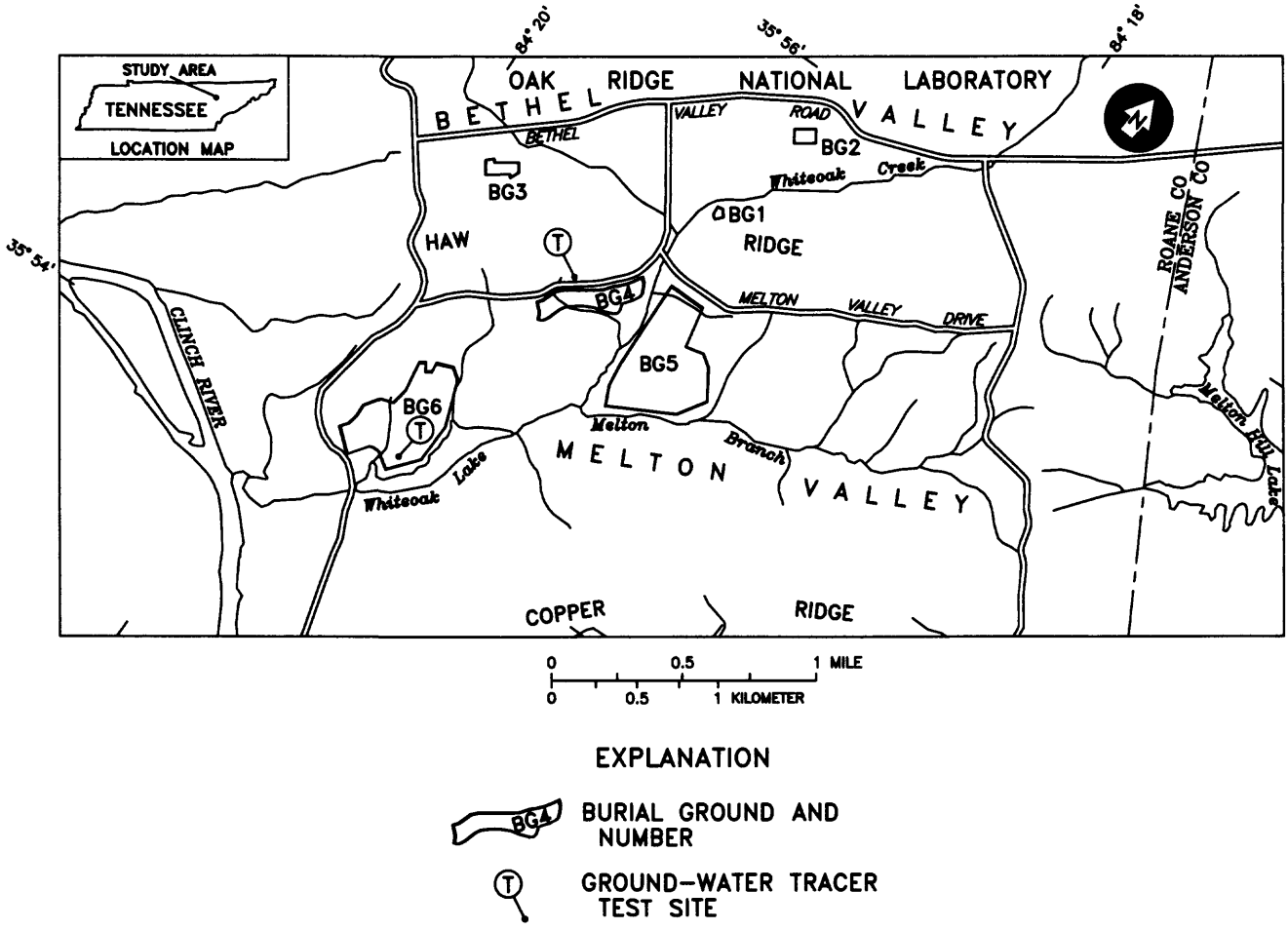


Figure 1. Location of the tracer-test study area.

ground water in the rocks underlying the disposal area flows preferentially in a direction parallel to formation strike, indicating that water flows mostly through fractures or partings between individual beds. This concept was applied to the flow of liquids from the pit system (deLaguna, 1956; Cowser and Parker, 1958) and later to the probable pathways of ground-water flow at the burial grounds (Lomenick and Wyrick, 1965).

As part of a U.S. Geological Survey (USGS) study to help define the hydrology of the burial grounds, ground-water tracer tests were conducted at and near two burial grounds from 1977 to 1982 to further examine this concept. The objective of the tests was to determine if rock weathering in the regolith had progressed sufficiently to permit water to flow through joints that had developed in the beds, that is, in a direction transverse to the bedding and formation strike. The tests were limited to the regolith, through which most ground-water flow occurs (Webster and Bradley, 1988; Solomon and others, 1992a, 1992b; Tucci, 1992). The tests were prompted by (1) the apparent exclusion of regolith from consideration in most of the earlier studies of ground-water flow by casing wells to bedrock, and (2) doubts about the water-tight integrity of the weathered beds exposed in trench walls of burial ground 6, the operational site. Close inspection of walls of open trenches in that disposal site showed that the beds commonly had weathered to fragments and, therefore, contain numerous joints which seemingly could transmit water, assuming that this characteristic extends below water-table depth.

The conclusions of these tests were included in a report of the hydrology of the burial grounds (Webster and Bradley, 1988). This report presents the results in greater detail because of continuing studies and interest in the hydrology of the Oak Ridge Reservation, of which the Laboratory is part. This report describes the tests, presents the data collected, provides interpretation, and compares the results with the results of other investigators who also have conducted ground-water tracer tests in the area.

The report is partly an outgrowth of a status report on the study of the Reservation hydrology, presented at the Fifth Tennessee Water Resources Symposium (Solomon and others, 1992b). Subsequent discussions with Drs. D.D. Huff (ORNL), D.K. Solomon (University of Utah, formerly with ORNL), and Larry McKay (University of Tennessee) concerning the tracer-test results and the evidence that they offer to support the concept of matrix diffusion added impetus for this report, and are especially acknowledged. The study of the burial-ground hydrology was conducted in cooperation with the U.S. Department of Energy.

HYDROGEOLOGIC SETTING

Oak Ridge National Laboratory is located in the Tennessee section of the Valley and Ridge physiographic province, an area characterized by a series of northeast trending valleys and ridges extending from Alabama to Pennsylvania. Melton Valley, one of the shorter valleys of the region, is about 4-1/2 miles long and 1 mile wide. At the time the tests were being planned, four informal units of the Conasauga Shale (Cambrian age) in the valley had been described (Barnett, 1954). Geologic study after the tests had started led to the recognition, description, and mapping of six formations (table 1) of the Conasauga Group (Haase and Vaughn, 1981; Haase and others, 1985; Hatcher and others, 1992) (fig. 2). They are, in ascending order, the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. All except the Maynardville Limestone underlie the waste-disposal area.

The Pumpkin Valley Shale, lowermost of the six formations, underlies most of burial ground 4 and the adjacent area to the northwest where one of the tests was conducted. In the general vicinity of the test site, the Pumpkin Valley Shale consists of interbedded mudstone, shale, and siltstone. The lower unit of the Nolichucky Shale underlies the southeast half of burial ground 6 where the other test was conducted. This unit is a carbonate-rich shale consisting of alternating beds of shale and limestone (Haase and others, 1985).

The predominant structural feature of the area is the Copper Creek thrust fault, along which the fault block containing present-day Melton Valley was displaced over the adjacent fault block to the northwest. The compression caused moderate to intense deformation of the carbonate and clastic beds, resulting in numerous fractures, joints, faults, and folds. Regional strike is N 56° E, and dip of beds in the regolith and upper bedrock is to the southeast at angles commonly ranging from about 30° to 40°.

Regolith extends to as much as 60 feet depth below the low hills along the western side of the valley, and to perhaps 5 feet or less along drainages in

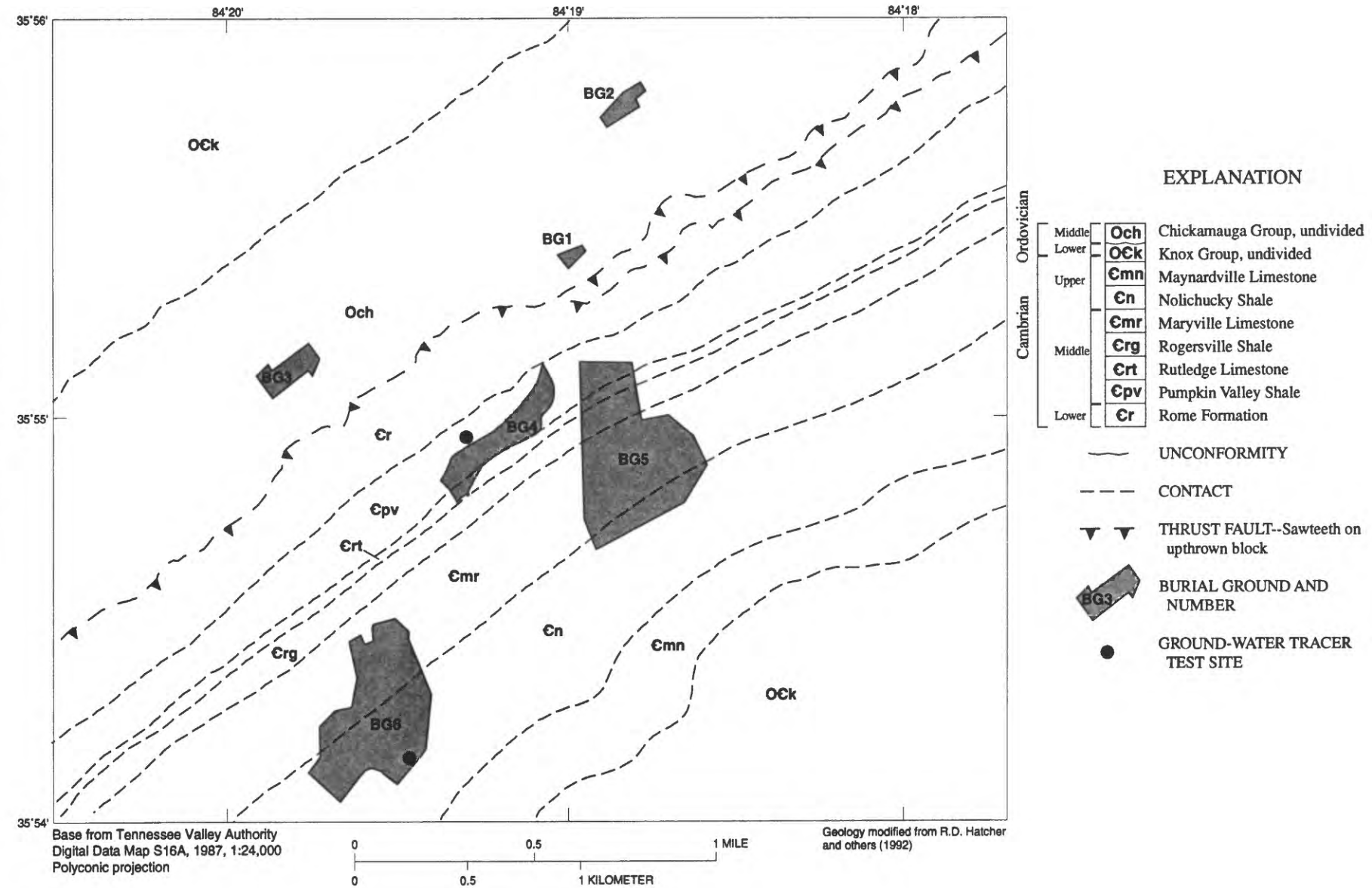


Figure 2. Geology of the Oak Ridge National Laboratory area, Tennessee.

Table 1. Overview of Conasauga Group lithology in the Oak Ridge National Laboratory area, Tennessee

[Based on study by Haase and others (1985) of the Joy No. 2 borehole, about 3-1/2 miles northeast of the burial ground 6 test site]

Maynardville Limestone	—Predominantly limestones. Thickness, 324 feet.
Nolichucky Shale	—(upper two units) Interstratified calcareous mudstone, limestones, and siltstone; (lower unit, includes area of tracer test in burial ground 6) alternating beds of shale and limestone. Thickness, 551 feet.
Maryville Limestone	—(upper unit) Limestone interbedded with subordinate amounts of calcareous mudstones; (lower unit), calcareous mudstones interstratified with limestones and calcareous siltstones. Except for the Maynardville Limestone, the upper unit contains the most pure carbonate rock of the Conasauga Group in the Oak Ridge area. Measured thickness, 463 feet, but because of deformation, true thickness is less.
Rogersville Shale	—Interbedded noncalcareous mudstones and siltstones; contains a 26-foot thick limestone unit. Thickness, 130 feet.
Rutledge Limestone	—Limestones interbedded with calcareous and noncalcareous mudstones and shales. Thickness, 101 feet.
Pumpkin Valley Shale	—Mudstones and shales interbedded with siltstones; lower unit (includes area of tracer test near burial ground 4) is slightly more siltstone rich than upper unit. Thickness, 309 feet.

Structural elements common to all of the formations are bedding-plane faults, high-angle faults, multiple joint sets, and small scale fractures. Intraformational thrust faults occur within the Maryville Limestone and Rogersville Shale. Folds have been observed in excavations in the Maryville Limestone (pit area and burial ground 6) and probably occur in other formations.

valley bottoms. Near land surface, the shale beds tend to be reduced to silt and the limestone beds to a silty clay, but in many places at only slightly greater depth, the beds are composed of weathered, *in situ* fragments of rock. Regolith exposed in trench walls at burial ground 6 and in the transuranic storage area of burial ground 5 commonly shows the bedding and structures of the original rock (fig. 3), a characteristic that would also apply to undisturbed areas. Regolith beds contain numerous joint or fracture sets. Three common orientations have been reported (Sledz and Huff, 1981; Solomon and others, 1992a): those parallel to bedding planes (between beds), parallel to strike (within beds), and more or less perpendicular to bedding planes (across beds).

The water table commonly occurs in the lower part of the regolith. Depth to the water table is related to topographic location and lithology, and may be as much as 50 feet near the hill tops and a few feet or less near drainages. Annual fluctuations in depth range generally from about 1 to 15 feet, depending on location.

In summarizing current understanding of the hydrologic system, Solomon and others (1992a) stated that most water in the saturated zone is transmitted through a layer, about 1 to 5 meters (3 to 16 feet) thick, of closely spaced connected fractures near the water table. The bulk of the water mass in this interval resides within porous matrix blocks between fractures.

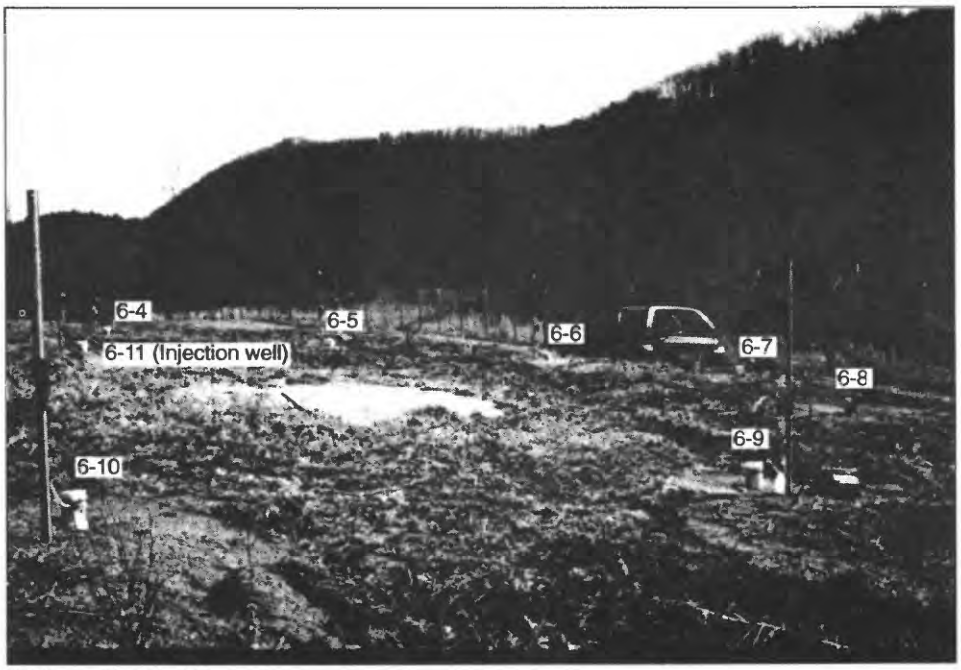
TRACER-TEST DESIGN

Two well fields were developed to examine the hypothesis that ground water in the regolith can flow transverse to the bedding. Criteria for selecting the sites were that each should be (1) outside of areas with ground water contaminated by previous investigations or waste-disposal operations, (2) underlain by the same geologic units that underlie the burial grounds, (3) readily accessible to a drill rig, and (4) on terrain suitable for a well field where the orientation of bedding-plane openings (which is the direction of formation strike) and the direction of the water-table gradient are approximately at right angles to each other.

Well-Field Characteristics

The first well field was developed in 1976 near the foot of a low hillock in burial ground 6 before much of that disposal site had been utilized for the burial of waste (fig. 4). The second well field was developed in 1977 on a hillside a short distance northwest of burial ground 4 (fig. 1). At each well field, eight test wells were constructed in a semicircular

Figure 3. Regolith beds exposed in west wall of a waste-burial trench at burial ground 6, January 25, 1979.



Wells are identified by number

Figure 4. Tracer-test site in burial ground 6. Equipment at wells was used in halocarbon tracer test prior to the tritiated-water tracer test.

pattern with the injection well (well 11) at the center. The seven observation wells were located radially at about 30° angles from the injection well and each other (fig. 5). A line passing through the two end wells of the semicircle (wells 4 and 10) also passed through the injection well and was oriented N 56° E, parallel to regional strike. The distance from the injection well to the observation wells in burial ground 6 was 30 feet. At the site near burial ground 4, the distance was decreased to 12 feet because the velocity of ground-water flow in the weathered Pumpkin Valley Shale was assumed to be less than that at the burial ground 6 site. Although the general configuration of the water table at burial grounds 4 and 6 was known in the planning of the well fields, the direction of the water-table gradient at each test site could not be determined until the wells had been completed. It was assumed that well 7, normal to strike along a line through well 11, would be located in line with the maximum water-table gradient—the maximum energy gradient—from the injection well. With this design, a tracer introduced at well 11 should be detected mostly in samples from wells 4 or 10 if ground-water flow occurs primarily between beds (that is, along strike), or at well 7 if the beds are sufficiently jointed or disintegrated to permit significant flow through them. In the latter case, later arrival times and smaller concentrations would also be expected in some of the other observation wells because of dispersion.

The wells at burial ground 6 were drilled with a hydraulic air-rotary rig. The injection well was about 29 feet deep, and the observation wells ranged from about 30 to 34 feet in depth. The bottom 5 feet of the injection well and the bottom 10 feet of the observation wells were screened. The wells near burial ground 4 were augered. The injection well was about 21 feet deep, and the observation wells ranged from about 27 to 31 feet in depth. All of the wells at this site had open bores from 5 feet in depth to terminal depth. Rock resistant to augering, perhaps the top of bedrock, was encountered at a depth of 27 feet at well 4-7 and precluded further penetration at that well site. Other construction details for the wells are given in table 2.

Cuttings from below water-table depth at the two well fields were different in composition and texture, reflecting differences in the parent rock, extent of weathering, and construction method. At burial

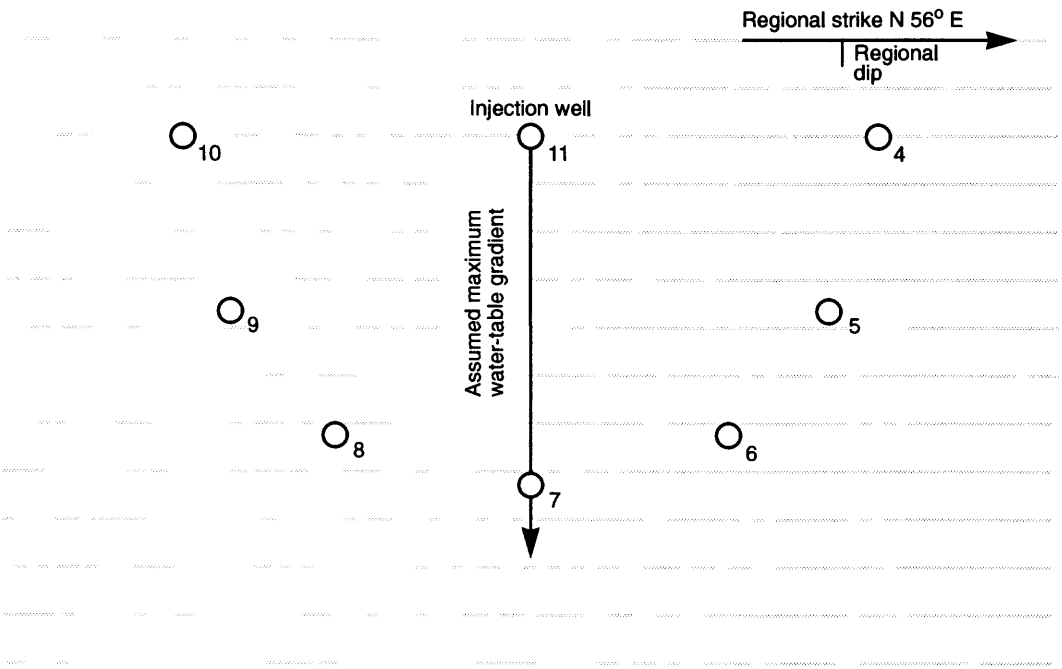


Figure 5. Well-field design.

Table 2. Construction details of tracer-test wells

[Depths are in feet below land surface]

Well no.	ORNL coordinates (north)	ORNL coordinates (east)	Approximate land-surface altitude	Completed depth	Depth to water, July 12, 1977	Remarks
			Site near burial ground 4			
4-4	19548	27777	843.3	30.0	16.26	
4-5	19542	27776	842.4	28.9	16.01	
4-6	19538	27772	841.5	29.4	15.22	
4-7	19536	27765	840.8	27.1	14.91	Hard rock at 27 feet
4-8	19537	27760	841.0	30.9	14.50	
4-9	19541	27756	842.3	30.8	15.26	
4-10	19547	27753	844.0	29.3	16.49	
4-11	19548	27765	843.5	20.8	16.42	
			Site in burial ground 6			
6-4	15882	24409	773.7	32.2	25.48	
6-5	15867	24405	772.5	30.5	24.31	Well terminated in a cavity
6-6	15855	24393	772.0	31.0	23.79	
6-7	15851	24378	772.1	30.7	23.94	
6-8	15856	24363	772.4	30.6	24.13	
6-9	15867	24352	772.9	32.0	23.76	Cuttings contained much clay
6-10	15881	24348	774.1	34.2	25.43	
6-11	15882	24379	774.7	29.3	25.76	

Boreholes were augered with an 8-inch-diameter auger to 5 feet in depth and cased with 6-1/2-inch outside-diameter polyvinylchloride (PVC) pipe which was grouted in place. Holes were deepened with a 5-inch-diameter auger to terminal depth. Completed wells had open bores from the bottom of the casing to the bottom of the bore. Casings were covered with tight-fitting PVC caps. Because of slope, driller offset well 4-7 southwesterly from planned location by about 5° from injection well. Auger cuttings from below nominal water-table depth consisted of very friable silt and clay clumps containing small particles of weathered rock.

Holes were drilled by a hydraulic air-rotary rig with an 8-inch-diameter bit. A 10-foot long, 4-1/2-inch outside-diameter, steel, die-stamped screen, coated with epoxy paint, and packed with pea gravel, was installed in wells 6-4 through 6-10. A similar screen of 5-foot length was installed in well 6-11. Screens were attached to 4-1/2-inch outside-diameter PVC pipe, which extended a short distance above land surface and had tight-fitting PVC caps. Annulus above pea gravel in each well was filled with drill cuttings. Driller reported that "rock" began at about 15-foot depth—this was a resistant bed but is not considered the top of bedrock. Drill cuttings below water-table depth consisted mostly of rock chips with some clay. Drilling technique could have blown or washed away more fine-grained particles than was apparent in samples of the cuttings.

ground 6, the cuttings consisted primarily of limestone and silty limestone chips with some clay, whereas at the site near burial ground 4, the cuttings consisted of silt, clay, and small fragments of rock. Based on this observation, regolith of the latter site appears to have undergone greater decomposition and probably had greater porosity than that of the burial ground 6 site.

Tracer

Tritiated water—that is, water in which the radioactive gas, tritium, has been dissolved—was used as a tracer. Tritium is an isotope of hydrogen and has a half life of 12.4 years. When dissolved in water, tritium (^3H) becomes incorporated in the water molecule by replacing one of the protium (^1H) atoms. Aside from having a small difference in vapor pressure, tritiated water has characteristics that are generally similar to untritiated water (Jacobs, 1968, 1974).

Several laboratory and field studies have been made to evaluate the use of tritiated water as a tracer. Some of the laboratory studies have indicated that the flow of tritiated water through clay soils may result in retardation of the tritium front. Retardation has been attributed to the exchange of tritiated water with the bound water of soil (Kaufman and Orlob, 1956a, 1956b) and to the exchange of tritium ions with hydrogen or hydroxyl ions of clay (Stewart and Stetson, 1975). Nevertheless, field studies prior to these tests generally have indicated that the flow of tritiated water through geologic media occurs at the same rate as untritiated water, and thus little or no retardation

occurs. In a review of literature reporting tritium applications as a tracer, Ames and Rai (1978) summarized their review by stating that even though some of the laboratory studies reported selective fixation of tritiated water on clays, all of the field studies have indicated that movement of the tritium front in water is synonymous with water movement. It is this characteristic—the ability to measure ground-water flow velocity at the waste-disposal sites—that made tritiated water especially attractive for use as the tracer in these tests.

About 50 curies (Ci) of tritium dissolved in water were released in the injection well near burial ground 4 on July 13, 1977, and about 100 Ci in the injection well at burial ground 6 on July 14, 1977. The device used for adding the tracer to the well near burial ground 4 was fabricated in accordance with a design provided by one of the ORNL safety officers. It was a long, 2-inch-diameter steel pipe, perforated from top to bottom, with a plate welded to its bottom end. A cylinder inside the pipe was raised by pulling a rope and allowed to free fall by gravity to break the small vial of tracer fastened to the inside surface of the bottom plate. The concept seemed simple, but many attempts were required to break the vial. Each traverse of the cylinder acted as a surge block in the open bore, and caused the borehole wall to slough and make the water extremely turbid. Because of the difficulty experienced at this site, a different method, based on the recommendation of the health physicist attending the injections, was used at burial ground 6. Strings were attached to the top and bottom of the vial, the cap was removed, the vial was lowered into the well on one string, and after reaching the water surface, the vial was inverted by pulling the other string to release its fluid. The fluid was mixed with the well water by inserting in the well a long steel rod with a circular disc fastened to its bottom end, and running the disc through the water column a few times.

Although the amounts of tritium dissolved in the tritiated water were substantial, the amount of fluid added to each well was small. Consequently, addition of the fluid to the well water did not measurably raise the water level in the wells, and the tests were initiated and conducted under natural gradients.

Sampling and Analysis

A pair of rubber gloves and a 60 milliliter (mL) separatory funnel were dedicated to each well for the purpose of sampling. Each separatory funnel had a length of heavy string tied to its neck and a piece of lead rope wound around its bottom end to provide enough weight for submergence. Sampling was done by lowering the funnel through the entire water column in the well before withdrawing the vessel. Because of the constricted neck, filling of the funnel took several seconds, and the sample obtained therefore represented water from much, if not all, of the water column. After retrieving the funnel, the stopcock was opened, and the entire sample allowed to flow into a small-volume sample bottle supplied with a water-tight cap, with the excess volume of sample spilling back into the well. The separatory funnels were stored inside the well casings when not being used.

Samples were first collected about 10 days before the tests began in order to determine background concentrations of tritium in the water of each well. Samples were collected from all wells again shortly before the injections, and from the injection wells only, immediately after introducing the tracer to determine the concentrations of tracer in each injection well. Sampling frequency varied thereafter, decreasing from daily or nearly daily at the beginning of the tests, to about twice monthly after 1-1/2 years, followed by one sample annually for the next 3 years.

The samples were prepared by mixing 1 mL of sample with 15 mL of scintillation cocktail on a laboratory bench equipped with an exhaust hood. Samples collected during the first week after injection were analyzed in an ORNL Environmental Sciences Division laboratory, but because of questionable results, these samples were again analyzed, as were all subsequent samples, at a laboratory in the Analytical Chemistry Division (ACD). Counting efficiencies of each new batch of cocktail used in preparing the samples were calibrated in the ACD to tritium standards obtained from the National Bureau of Standards.

Occasionally, an analysis for a sample appeared questionable when compared to previous results for that well and a new sample was prepared, but in virtually every instance, the second analysis confirmed the results of the first one. In addition, duplicate samples for wells were prepared on many occasions and submitted with a later batch of samples as a quality-control check. Replications of the analyses with those for the earlier samples were close. For an independent check, samples collected on October 16, 1978, were also analyzed at the USGS Laboratory in Reston,

Virginia. The results from both laboratories for that day are shown in Appendix 2. The slight differences between laboratories probably result from the number of dilutions required to perform the analyses at Reston and from the statistical nature of radioactive decay.

Hydrologic Data

Hydrologic data collected during the study included water-level measurements at the wells, daily precipitation, and hydraulic conductivities. The water-level measurements were made on several occasions before the tracer was introduced and again 1 to 2 days before starting the tests. For 5 months after introducing the tracer, measurements were made only in wells 4 and 10 of each site, selected as representative of the sites. Later, all wells were measured on about a weekly basis for more than a year, and on a biweekly basis during months 21 through 24. To prevent cross-contamination of the wells, the steel tape used for measuring was rinsed with deionized water and wiped dry after each measurement.

Precipitation was measured with tipping-bucket rain gages maintained at two stations. One station was located in burial ground 5, about 0.5 mile southeast of the well field near burial ground 4, and the other was in burial ground 6, about 0.3 mile north of the well field in that site. The rain gages had mechanical failures from time to time. The precipitation data included in figures 6, 8, and 9 of this report are for the burial ground 6 station, except for February, March, and May 1979, which are for the station in burial ground 5 (Webster and others, 1982)

In 1980, after the period of intensive data collection at the well fields, hydraulic conductivities were estimated by performing slug tests of each well except well 6-11 which, at the time, had an insufficient amount of water. The determination of hydraulic conductivities was part of the larger study of the burial grounds. The results are included in Webster and Bradley (1988) and are repeated in Appendix 3 of this report.

RESULTS OF TRACER TESTS

During the period of the tests, about 3,500 samples of water from the wells in the two well fields were analyzed for tritium. The analytical data (unadjusted for radioactive decay) are given in Appendices 1 and 2, and graphs of the data for the first 2 years of sample collection are shown in figures 6, 8, and 9. The logarithmic scale of these illustrations allows placing data for all of the observation wells at each site on a common graph, but because of the great range in values, fluctuations at the high end of the scale are not as apparent as those at the low end. Therefore, data for those wells at which larger concentrations of tritium were detected are also shown on differing arithmetic scales, and to show the entire record, the period is extended to include data for the samples collected annually to 1982 (figs. 7 and 10).

During the 5-year period, the minimum detection level varied from ≤ 6 to 96 disintegrations per minute per milliliter (dpm/mL) of sample. An approximate daily minimum detection level is indicated in figures 6 and 9 by a broken dotted line representing the maximum daily value that one or more samples from either site had a concentration reported as "equal to or less than." Breaks in the line indicate intervals when all samples from both sites contained measurable concentrations.

For the first several days after the injections, tritium was detected in measurable concentrations in samples collected from all of the wells. Initially, it appeared that the liquid spectrometer used for the analyses was defective and producing erroneous values, but the detection in a different spectrometer of significant concentrations of tritium in the urine of personnel engaged in releasing the tracer and sampling the wells implied that atmospheric contamination of samples and personnel was occurring. Because rubber gloves were worn at all times when the samples were collected and prepared, the most probable pathway for body intake of tritium seemed to be by inhalation. To determine if gaseous transfer to the atmosphere was the likely mechanism for contamination, two large Erlenmeyer flasks were cleaned and each equipped with a stopper, valve, and short length of tubing. Ten milliliters of deionized water were placed in each flask and the air in the flasks was evacuated. The tubing attached to one flask was placed in the air space of well 6-1, a capped well in burial ground 6, about 120 feet north of the injection well, and the valve on the flask was opened to draw in an air sample. In similar fashion an air sample was obtained from well 6-11, the injection well. The air sample was then mixed with the deionized water in each flask and the solution allowed to equilibrate over a 24-hour period. Analyses for tritium are shown in table 3.

Table 3. Tritium analyses to determine mechanism for sample contamination

	Concentration, in disintegrations per minute per milliliter
Deionized water only	≤6
Deionized water mixed with air from well 6-1.	≤6
Deionized water mixed with air from well 6-11.	1.13×10^7

These results revealed that tritium in water at the injection well was diffusing to the air space in the casing, and demonstrated the potential for contamination of samples by atmospheric transfer. Because all samples collected on July 13—before introducing the tracer to either well field—contained measurable concentrations of tritium, the place of contamination appears to have been in the laboratory where the samples were prepared for analyses. Samples collected from July 15 through July 19 and from well 6-5 on July 20 could have been contaminated in the field or in the laboratory. To minimize the potential for contamination of subsequent samples, the samples were prepared in a different laboratory and the two injection wells were not opened or sampled again until several weeks had passed. Later, when they were sampled, they were the last well in each well field to be sampled.

Site Near Burial Ground 4

After eliminating the probable contaminant pathway, tritium was detected, in time, in samples from all of the observation wells at the site near burial ground 4. The length of time for sustained concentrations (defined as two or more consecutive samples) to be detected at individual wells ranged from 9 days or less to 205 days (table 4). The sequence of arrival was wells 4-7, 4-6, 4-9, 4-8, 4-10, 4-5, and last, well 4-4. Water from well 4-7 contained tritium transported in ground water by the time the contaminant-preventive measures had been implemented and the next sample collected (9 days after injection). Concentrations slightly greater than the minimum detection level were measured occasionally in samples from well 4-4, but it was not until the 205th day that such concentrations were sustained in two or more consecutive samples.

Tritium Concentrations

Over the 5-year period of record, the largest concentrations of tritium were consistently detected in samples from well 4-7, the well that is normal to the injection well relative to formation strike (fig. 6). Although the leading edge of the plume arrived within 9 days, 5 to 6 months elapsed before concentrations began their rapid increase to maximum values, signalling arrival of the main part of the plume (fig. 7). The peak concentration, 8.82×10^6 dpm/mL, occurred on February 27, 1978, 229 days after the test began.

The second largest concentrations were detected in samples from wells 4-6 (1.10×10^6 dpm/mL) and 4-8 (2.38×10^6 dpm/mL), adjacent to well 4-7, and from well 4-9 (fig. 6). After breakthrough, concentrations at well 4-6 increased steadily over 5 months and at well 4-8 at a slower rate over 14 months before reaching maximum values. In contrast to the pattern characteristic of these wells, concentrations at well 4-9 had many peaks, the first one occurring within 12 days of arrival.

Table 4. Length of time after start of tests for sustained concentrations of tritium to be detected in samples from observation wells

Site near burial ground 4		Site in burial ground 6	
Well no.	Days	Well no.	Days
4-4	205	6-4	155
4-5	77	6-5	172
4-6	57	6-6	218
4-7	9 or less	6-7	148
4-8	67	6-8	112
4-9	66	6-9	265
4-10	69	6-10	204

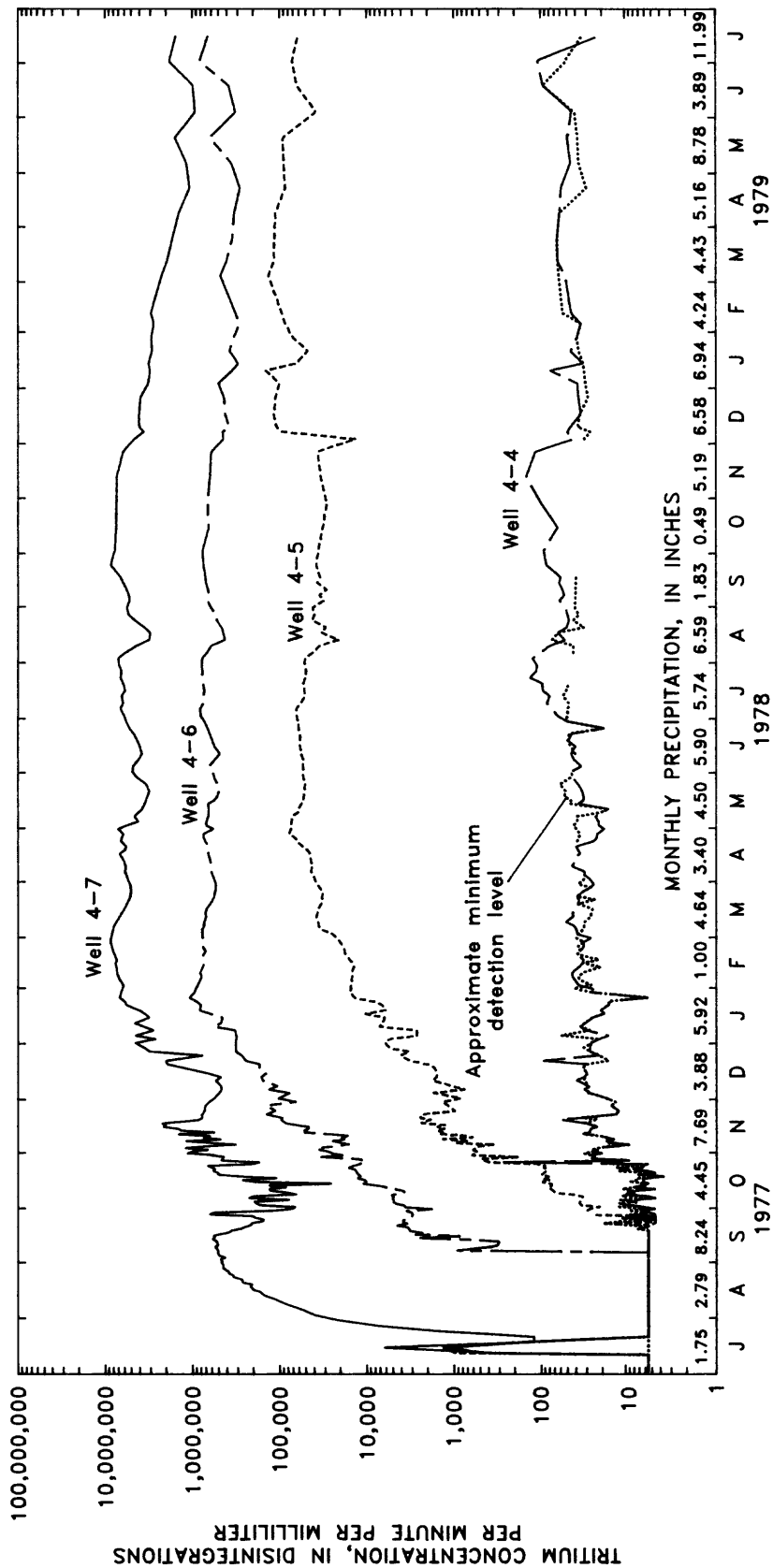


Figure 6. Tritium concentrations in water from observation wells at site near burial ground 4, 1977-1979.

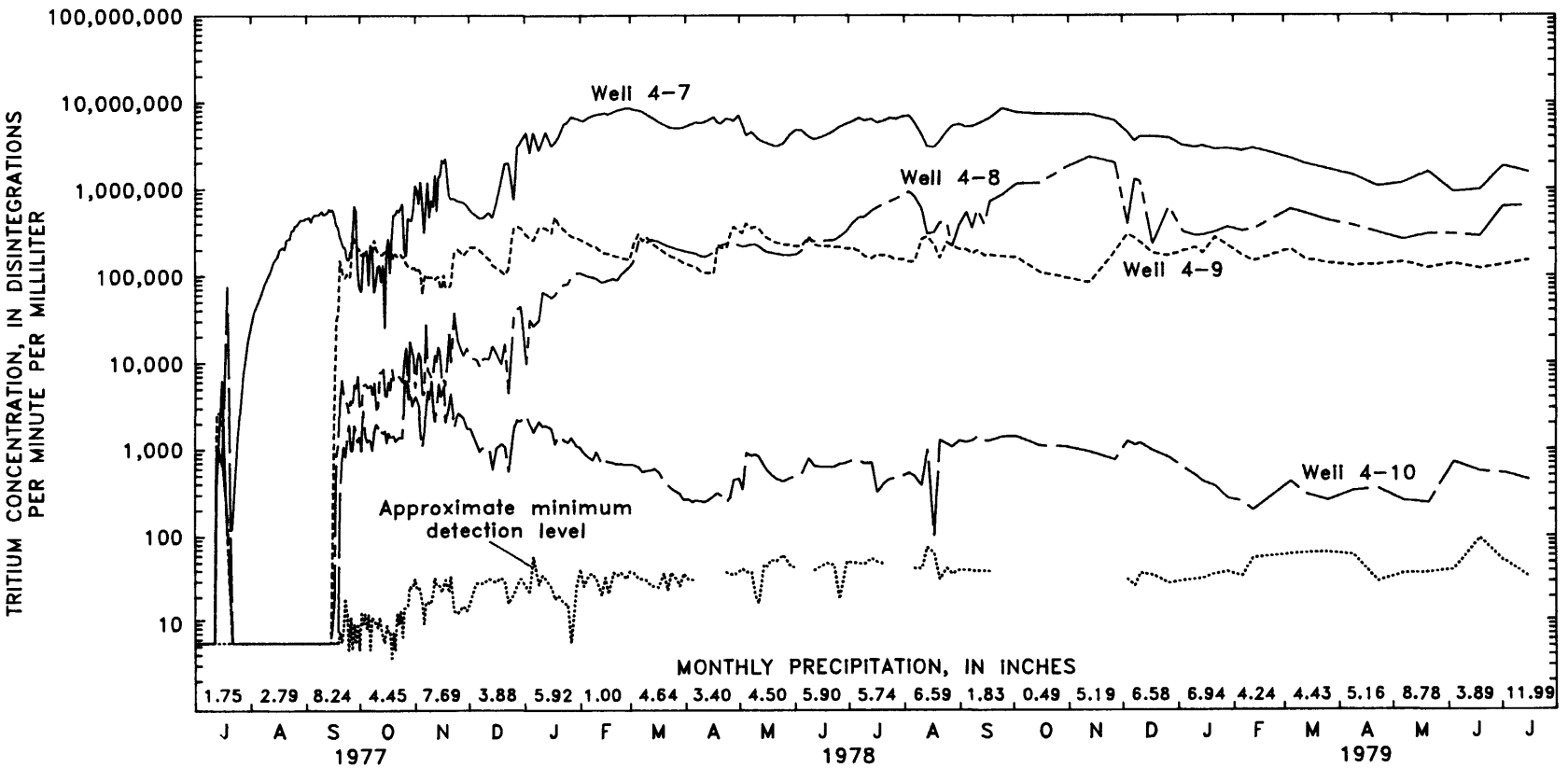


Figure 6. Tritium concentrations in water from observation wells at site near burial ground 4, 1977-1979—Continued.

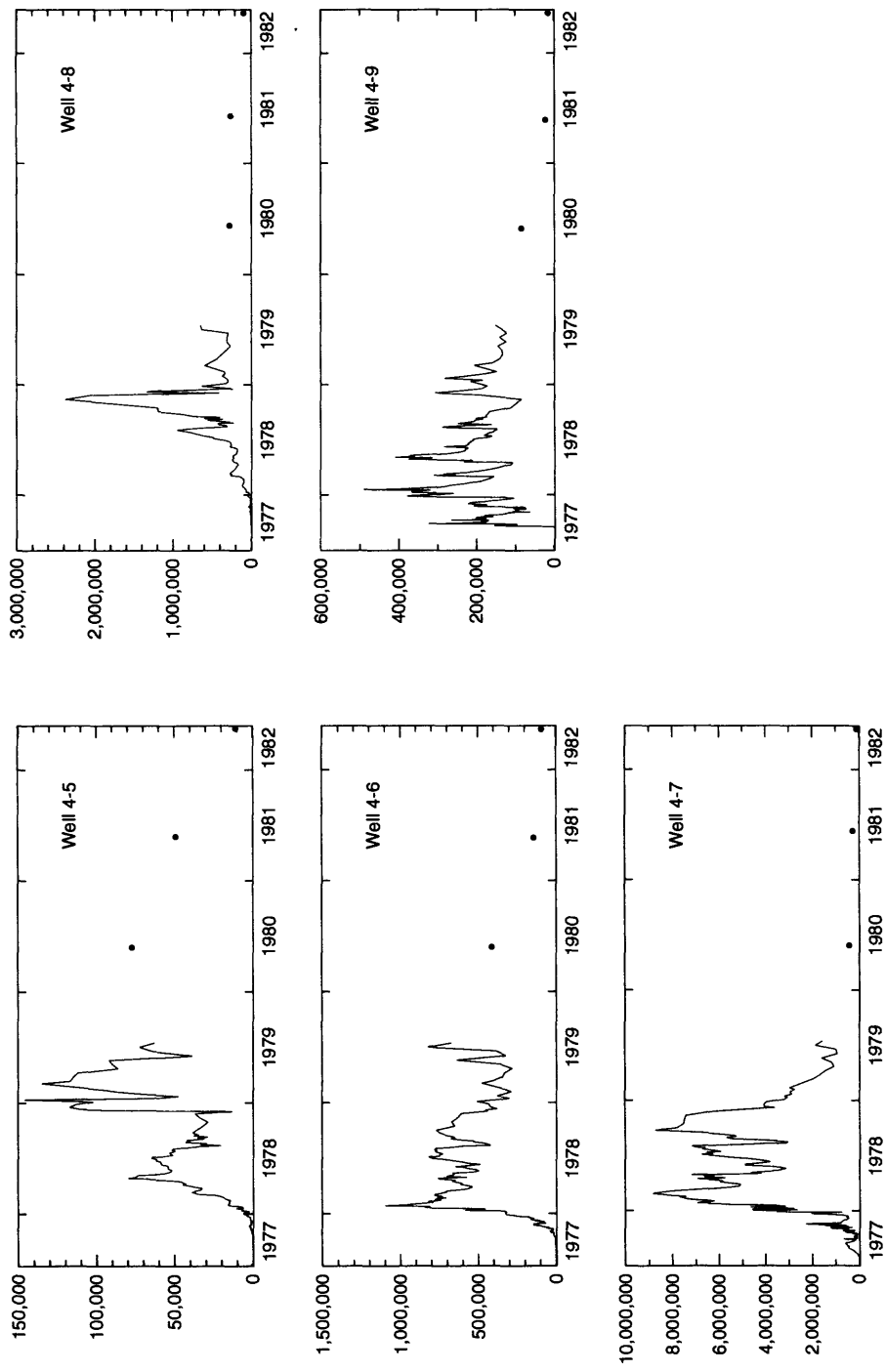


Figure 7. Tritium concentrations in water from selected wells at site near burial ground 4, 1977-1982.

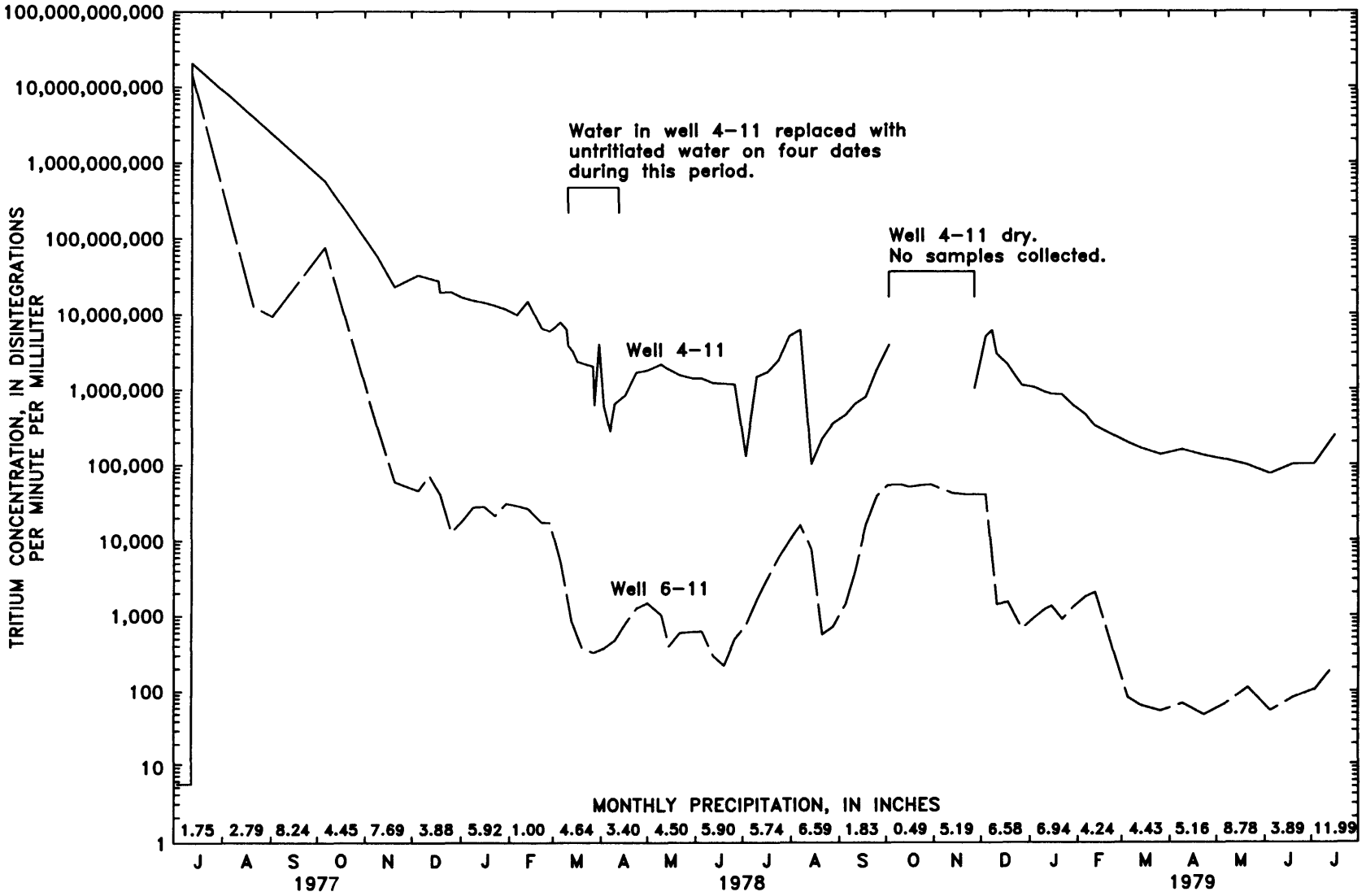


Figure 8. Tritium concentrations in water from injection wells, 1977-1979.

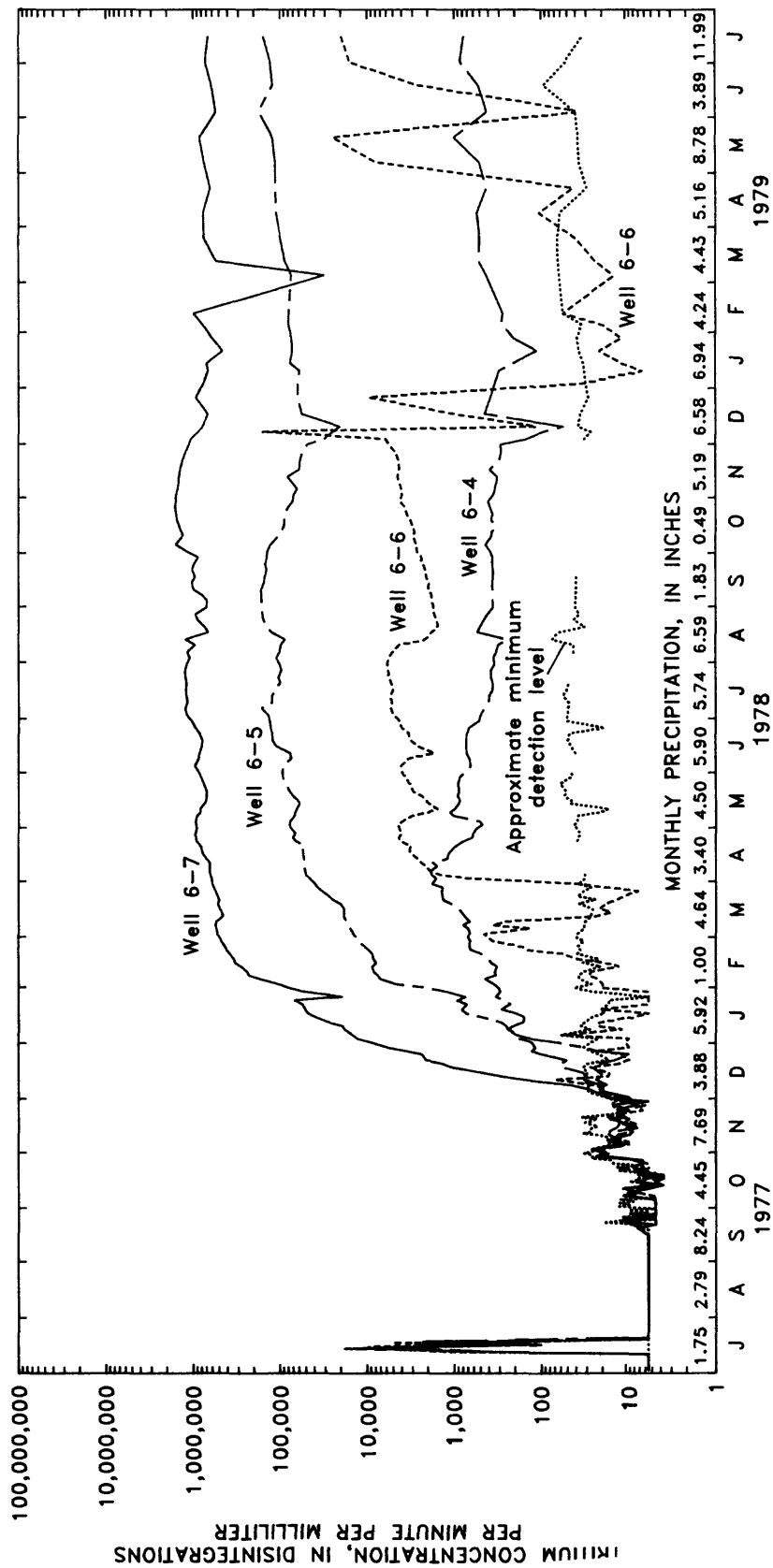


Figure 9. Tritium concentrations in water from observation wells at site in burial ground 6, 1977-1979.

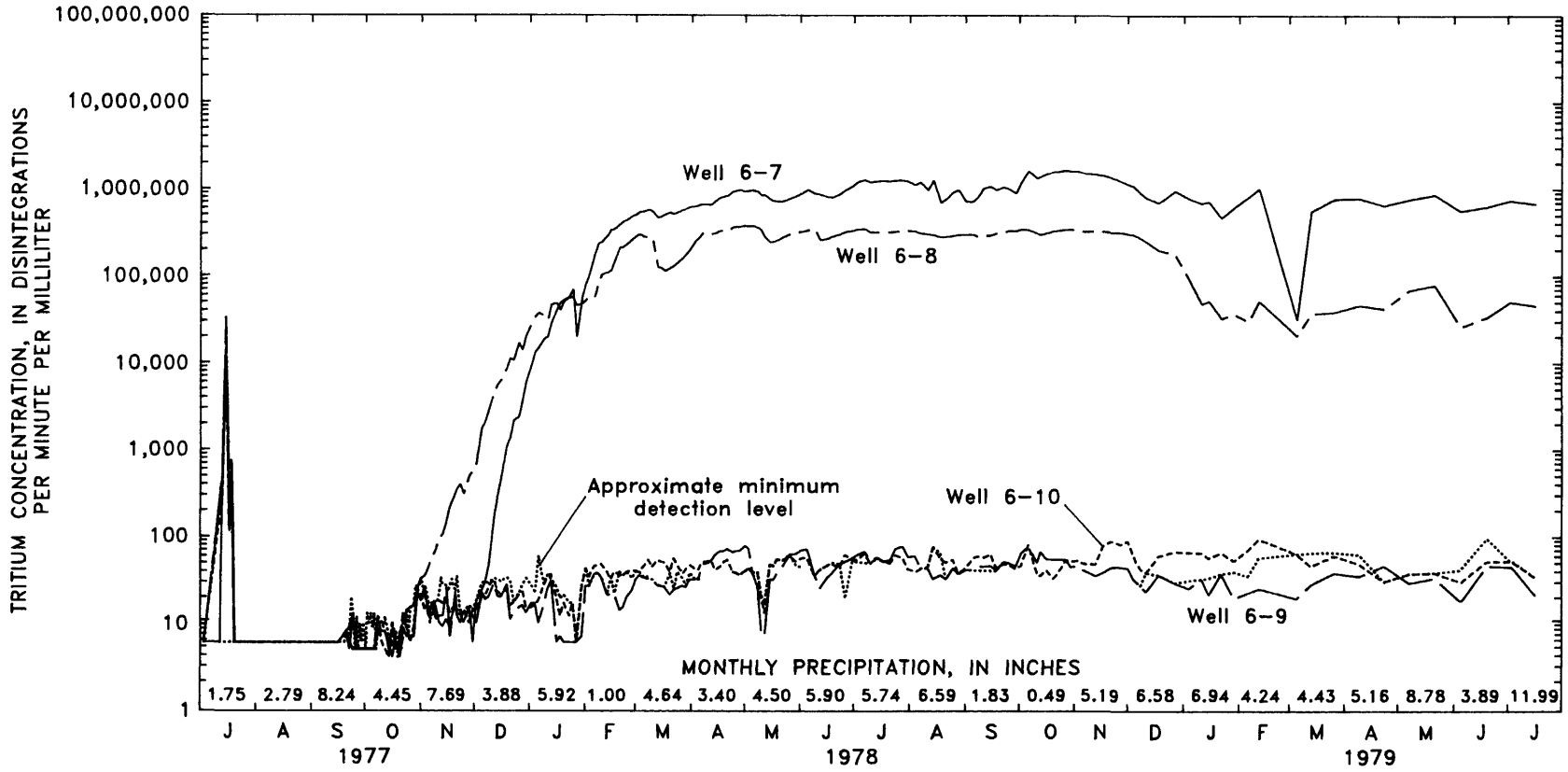


Figure 9. Tritium concentrations in water from observation wells at site in burial ground 6, 1977-1979—Continued.

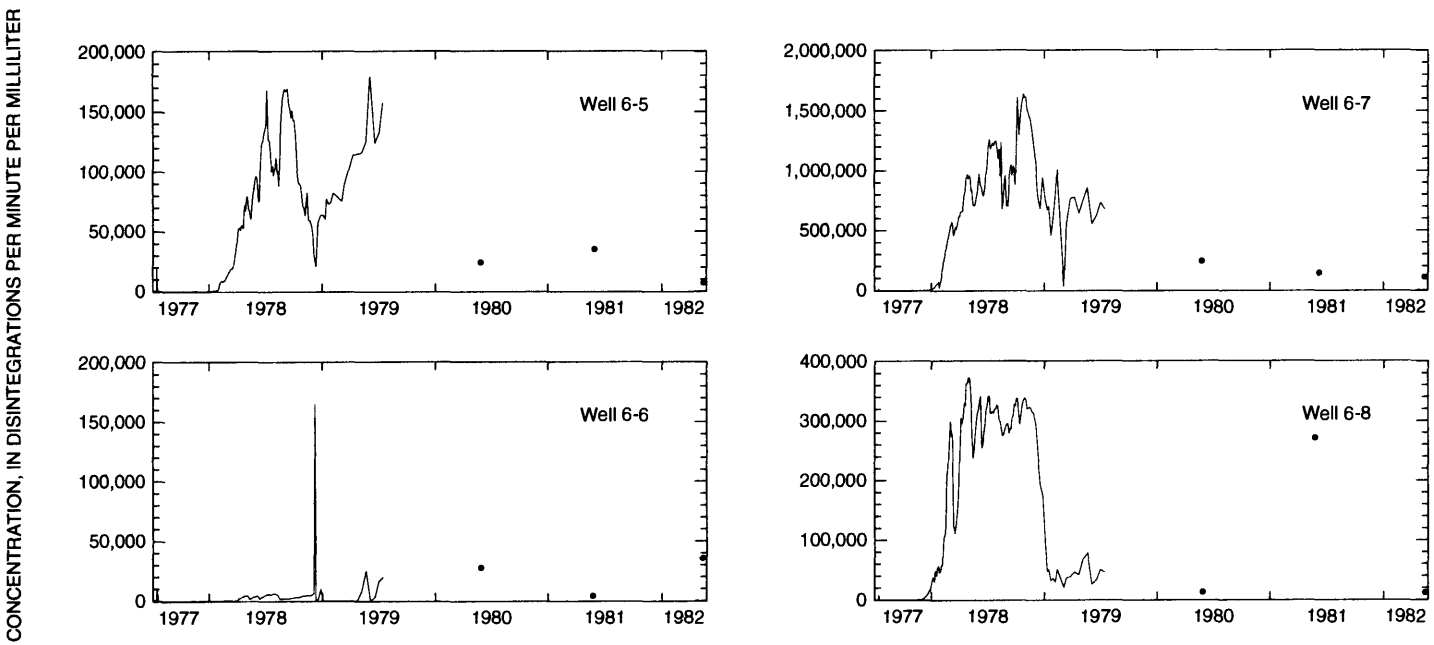


Figure 10. Tritium concentrations in water from selected wells at site in burial ground 6, 1977-1982.

Breakthrough at well 4-5 occurred later than at any of the preceding wells. The plume appears to have come in two pulses (fig. 7). The first pulse in winter and spring of 1978 was followed by a second pulse having twice the concentration during the winter of 1978-79.The smallest concentrations of tritium were measured in samples from wells 4-4 and 4-10, the two wells oriented parallel to formation strike relative to the injection well. Concentrations at well 4-4 generally remained at or below detection level until July 1978, 1 year after releasing the tracer, and slightly above detection level for the remainder of the test period except during the winter months of 1979. At well 4-10, concentrations rose to their maximum value (6.49×10^3 dpm/mL) about 1 month after the tracer first appeared and then gradually declined.

The initial concentration at well 4-11, the injection well, was 2.06×10^{10} dpm/mL (fig. 8). Twelve weeks later, the concentration was 5.73×10^8 dpm/mL, or about 2.9 percent of the original concentration. Concentrations continued a rapid but decreasing rate of decline until spring 1978, after which they wavered. Increases generally corresponded to periods of net discharge from the ground-water reservoir, whereas decreases generally corresponded to periods of net recharge. No samples were collected during an 8-week period of fall 1978, because the water level had receded below the bottom surface of the well, which had decreased in depth owing to siltation that resulted largely from the injection procedure. After the water-level recovery, the concentration declined from a peak of about 6×10^6 dpm/mL in December 1978 to about 7×10^3 dpm/mL in May 1982.

Long-term residual concentrations were characteristic of all of the wells. They are shown by the long tails that would result in figures 7 and 10 if the data points from July 1979 to May 1982 were connected.

Water-Table Gradient

The water-table configuration for the site near burial ground 4 is shown by the two maps of figure 11. The first map represents conditions on July 12, 1977, the day before the test at this site began, and is typical of conditions during summer and fall. The second map is for January 23, 1978, and is typical of conditions during winter and spring. On both maps an imaginary flow line through the injection well would be drawn south-southeasterly and pass between wells 4-6 and 4-7 at a point close to well 4-7, and would indicate the general direction of tracer flow from the injection well if the regolith below water-table depth were weathered to a porous isotropic medium. The change in direction of contour curvature on the winter-spring map might imply a tendency for greater dispersion of the tracer during those seasons.

To provide quantitative information on the direction and magnitude of the water-table gradient relative to the injection well, about half of the water-level data collected, considered representative of the entire period, have been converted to values showing the difference in water-level altitudes between the injection well and the observation wells (table 5). At the beginning of the test, the maximum gradient from well 4-11 was toward well 4-7. The difference in water-level altitudes between the two wells was 1.11 feet, equivalent to a slope of 8.9 feet per hundred feet. Smaller differences were characteristic of the other wells, and minimum differences were associated with wells 4-4 and 4-10.

The water table continuously adjusted in response to recharge. The data of table 5 reflect gradients from well 4-11 to well 4-7 ranging from about 5 to 30 feet per hundred feet, and occasional temporary shifts in maximum gradient from well 4-7 toward adjacent wells 4-6 or 4-8. Throughout the test, the smallest gradients from the injection well were consistently toward wells 4-4 and 4-10.

Site in Burial Ground 6

Tritium was detected in samples from all of the observation wells at the burial ground 6 site also. The tracer was first detected in water from well 6-8, then, in sequence, wells 6-7, 6-4, 6-5, 6-10, 6-6, and last, well 6-9. The length of time for sustained concentrations to be found in samples from individual wells after releasing the tracer to well 6-11 ranged from 112 to 265 days (table 4).

Tritium Concentrations

The largest concentrations of tritium were detected in water from well 6-7, the well normal to strike (fig. 9). Although breakthrough at this well did not occur until 5 weeks after breakthrough at well 6-8, once it did occur, concentrations increased rapidly. A maximum value of about 1.6×10^6 dpm/mL was reached during the 16th month of the test (fig. 10). The second and third largest concentrations were measured in samples from well 6-8 (about 3.7×10^5 dpm/mL) and well 6-5 (about 1.8×10^5 dpm/mL), respectively.

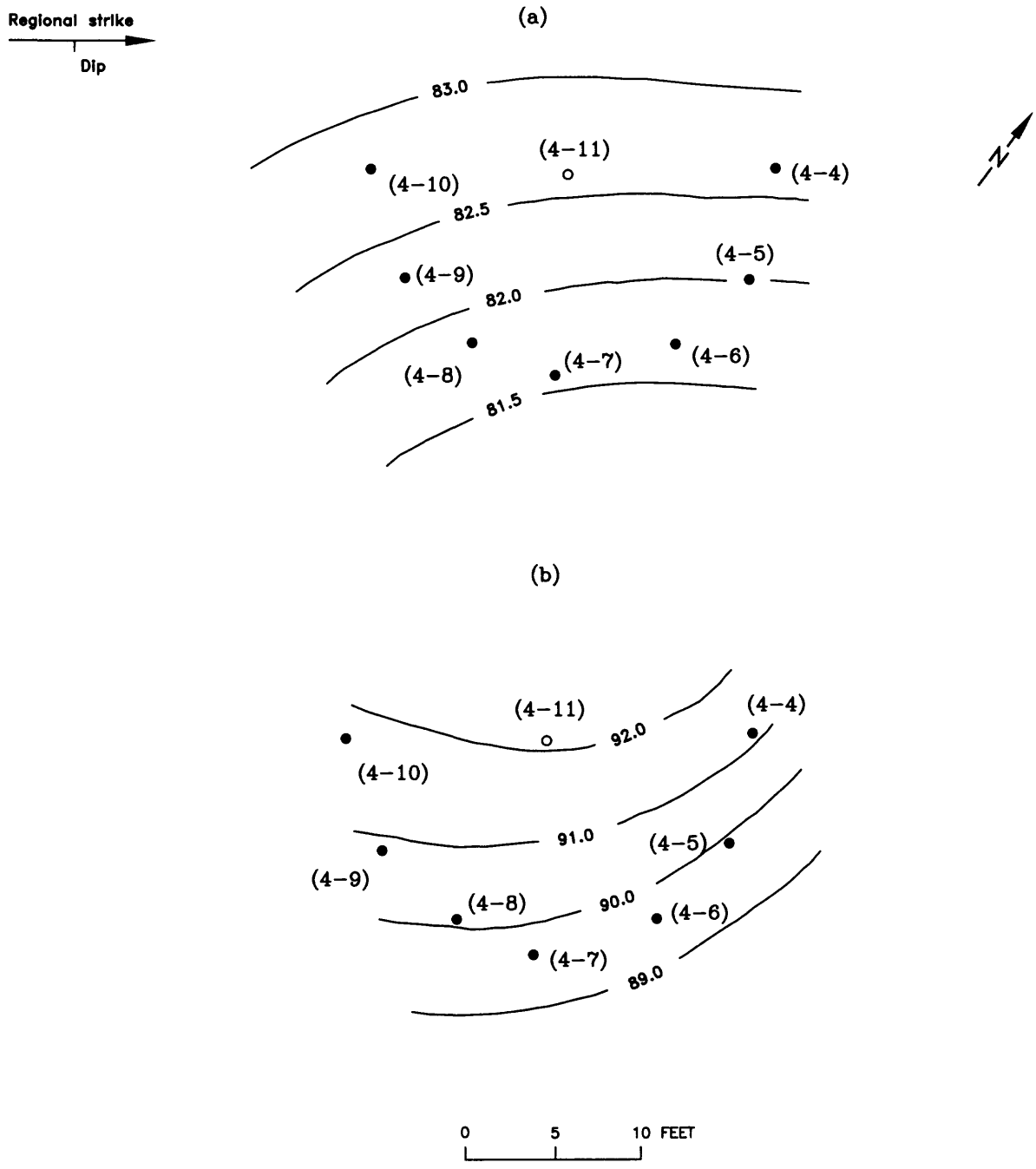


Figure 11. Water-table configuration at the site near burial ground 4 for (a) July 12, 1977 and (b) January 23, 1978.

Table 5. Difference in water-level altitudes between injection well 4-11 and observation wells

[Values are in feet. Minus sign indicates that water-surface altitude in observation well was greater than that of injection well. Rainfall data were recorded at gage in burial ground 6, except values with an asterisk, which were recorded at gage in burial ground 5 (Webster and others, 1982)]

	Observation well							
Date	4-10	4-9	4-8	4-7	4-6	4-5	4-4	Remarks
7-12-77	-0.13	0.29	0.79	1.11	0.76	0.65	0.00	Measurement made day before injection.
12-05-77	-.07	.81	2.32	2.18	2.09	2.15	1.46	0.97 inch rain on 12-04 and 12-05.
12-19-77	.44	.75	1.39	1.69	1.65	1.53	.63	
1-03-78	.42	.77	1.29	1.75	1.68	1.48	.59	
1-18-78	-.43	.55	2.24	2.38	2.26	2.25	1.07	0.90 inch of rain on 1-17 and 1-18.
1-23-78	.44	1.12	2.03	2.53	2.41	2.09	1.01	
1-30-78	.55	1.09	1.70	2.22	2.17	1.84	.94	1.89 inches of rain from 1-24 through 1-27.
2-13-78	-.20	.44	1.07	1.52	1.33	1.16	.13	
2-27-78	.09	.59	1.23	1.67	1.49	1.29	.20	
3-13-78	.41	1.21	2.32	2.68	2.56	2.33	1.29	1.87 inches of rain from 3-08 through 3-10.
3-27-78	.27	.67	1.33	1.66	1.59	1.52	.61	
4-10-78	-.06	.63	1.16	1.68	1.48	1.28	.22	
4-24-78	.21	.62	1.18	1.68	1.58	1.40	.38	
5-10-78	.20	1.12	2.20	2.50	2.40	2.24	1.36	0.95 inch of rain on 5-08.
5-22-78	.43	.64	.82	1.27	1.21	1.00	.22	
6-05-78	-.23	.36	.90	1.36	1.10	.88	.11	1.20 inches of rain on 6-02.
6-19-78	.08	.53	.93	1.41	.77	1.01	.08	
7-03-78	-.32	.35	.96	1.43	1.14	.88	.10	
7-17-78	-.68	.03	.66	.90	.72	.40	.27	2.91 inches of rain on 7-15 and 7-16.
7-31-78	-.51	.16	.66	1.02	.71	.45	.37	
8-14-78	1.39	1.56	2.33	2.70	2.77	2.45	1.75	4.95 inches of rain from 8-04 through 8-14.
8-28-78	.09	.53	.88	1.29	1.08	.81	.08	0.94 inch of rain on 8-25 and 8-26.
9-11-78	-.35	.25	1.00	1.05	.74	.44	.30	1.23 inches of rain on 9-10 and 9-11.
9-25-78	-.42	.25	.74	1.07	.70	.46	.37	
10-11-78	-.44	.33	.83	1.16	.67	.52	.31	Injection well dry 10-23-78 through 11-22-78.
11-27-78	-.51	.14	.48	.58	.50	.43	-.19	1.29 inches of rain 11-22 through 11-24.
12-11-78	.80	1.44	3.08	3.44	3.43	3.08	1.99	2.19 inches of rain on 12-04 and 12-05. 2.15 inches of rain 12-07 through 12-10.
12-27-78	.72	.98	1.48	1.79	1.97	1.72	.86	
1-11-79	.83	1.24	1.82	2.37	2.36	2.06	1.29	2.03 inches of rain on 1-06 and 1-07.
1-22-79	-.15	1.54	3.46	3.64	3.44	3.20	1.56	2.45 inches of rain from 1-19 through 1-22.
2-06-79	.36	.92	1.33	1.94	1.76	1.46	.44	
3-05-79	.03	1.47	3.11	2.98	2.82	2.69	1.55	*2.35 inches of rain on 3-03 and 3-04.
3-26-79	.83	1.30	2.15	2.52	2.44	2.28	1.35	*1.07 inches of rain on 3-23 and 3-24.
4-09-79	.51	.75	1.21	1.43	1.34	1.32	.75	
4-23-79	.36	.79	1.01	1.54	1.41	1.17	.26	
5-07-79	.97	1.14	1.42	1.92	1.87	1.68	.95	1.39 inches of rain on 5-03 and 5-04.
5-21-79	-.30	.31	.93	1.19	.99	.80	.12	1.16 inches of rain on 5-20 and 5-21.
6-04-79	.33	1.37	2.66	2.62	2.54	2.44	1.70	4.03 inches of rain from 5-31 through 6-03.
6-19-79	-.05	.58	.95	1.60	1.34	1.09	.05	
7-02-79	-.43	.40	1.08	1.59	1.25	.96	.05	
7-16-79	.31	1.09	2.69	2.33	1.25	2.41	.10	4.72 inches of rain from 7-07 through 7-15.
6-02-80	-.02	.31	.63	1.12	.93	.76	.13	
5-26-81	.08	.28	.93	1.82	1.41	1.09	.24	

More modest concentrations were characteristic of samples from wells 6-4 and 6-6. At well 6-4, one of the wells along strike from the injection well, the concentration peaked (about 2 x 10^3 dpm/mL) nearly 9 months after injection and then gradually declined. At well 6-6, concentrations increased slowly to reach a maximum of about 6 x 10^3 dpm/mL a year after injection, and then displayed some unusual fluctuations during the following year.

Only small concentrations of tritium were detected in samples from wells 6-9 and 6-10. Concentrations at these two wells fluctuated from less than the detection level to slightly more than the detection level. When measurable, concentrations were consistently less than 1 x 10^2 dpm/mL.

The initial tritium concentration at well 6-11, the injection well, was 1.46 x 10^{10} dpm/mL. The concentration decreased at a faster rate than at the injection well near burial ground 4, as is shown in figure 8 by the steeper slope. On October 6, 12 weeks after starting the test, the concentration was 7.57 x 10^7 dpm/mL, or about 0.5 percent of the initial activity level. Concentrations continued to decline until spring 1978, after which they wavered, generally paralleling the pattern of well 4-11. In the last sample collected in May 1982, the concentration had decreased to 6.6 x 10^1 dpm/mL.

Water-Table Gradient

The water-table configuration for the site at burial ground 6 on the same two dates as the previous site is depicted by the two maps of figure 12. The amount of contour curvature shown in the maps greatly exceeds that which would have been expected at the time the site was selected. The terrain appeared to have a fairly uniform, gentle slope to the southeast (fig. 4) which implied that the water-table contours would be fairly straight and aligned generally parallel to topographic contours and formation strike.

The map for July 12, 1977, represents conditions 2 days before the test at this site began and is typical of conditions during summer and fall. On this date the direction of maximum gradient from the injection well technically was to the southeast toward well 6-7, but the direction is not well defined because the contours are somewhat concentric around the injection well, and the difference in water-level altitudes between the injection well and wells 6-4 through 6-8 varied by only 0.09 foot. The map for January 23, 1978, typical of winter and spring conditions, shows an increased gradient and a somewhat greater range in differences of water-level altitudes, but little change in contour pattern.

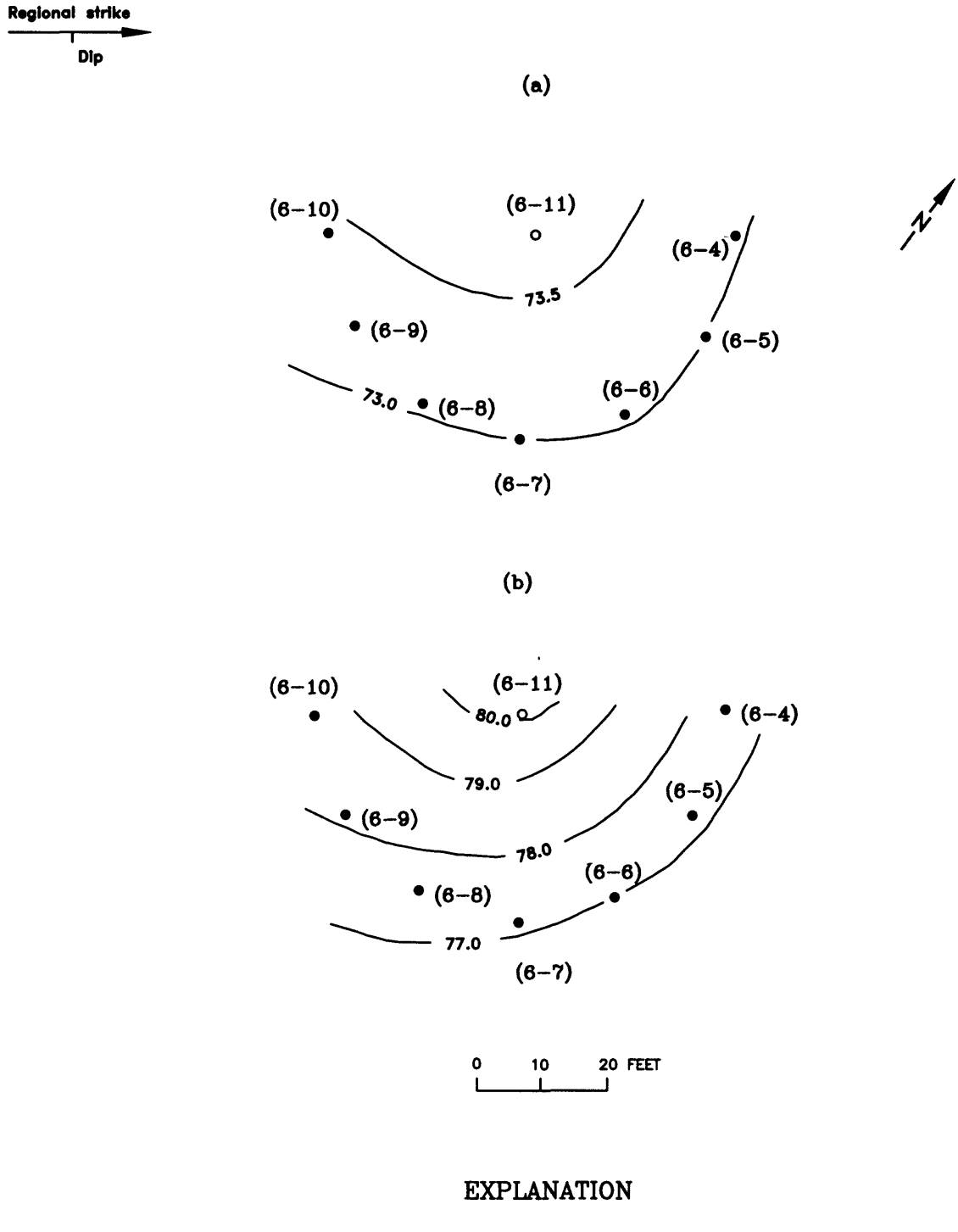
Additional data on the difference in water-level altitudes between the injection well and the observation wells are given in table 6. For most dates, the steepest water-table gradient from well 6-11 was toward well 6-7. The difference in gradient between the injection well and wells 6-6 and 6-7 usually was small, and on a few occasions the maximum gradient shifted to well 6-6. The shallowest gradients were associated with wells 6-9 and 6-10. For many dates, the altitude of the water surface in well 6-9 was higher than that of the injection well, which is an anomalous condition and which could indicate that well 6-9 was open to a water-bearing fracture having water under slight pressure. Because the water surface does not appear to represent the water table, the value for this well was discounted in preparing the two water-table maps. Anomalous water levels in this type of media are not unusual; they were found characteristic of at least a few other shallow wells drilled elsewhere into partly weathered rock in the waste-disposal areas (Webster and Bradley, 1987).

Two days before the test began, the difference between water-level altitudes in the injection well and well 6-7 was 0.83 foot. This is equivalent to a slope of 2.8 feet per hundred feet, or about one-third the gradient at the other site at the onset of the tests. During the period of the tests, the gradient increased during periods of rain, and reached a maximum of about 17 feet per hundred feet, and decreased during dry periods to reach a minimum of about 1.5 feet per hundred feet.

DISCUSSION

Flow Direction

The results of the tracer tests show that the greatest concentrations of tritium at each well field were detected in water from wells normal to the bedding and in line with the maximum or near maximum water-table gradient. This finding demonstrates that the regolith below water-table depth at each site has undergone sufficient decomposition and jointing to permit ground water to flow through the weathered beds, and that at these sites the direction of the water-table gradient is the primary factor controlling the direction of flow. Although earlier studies showed that the orientation of bedding-plane openings is a major



EXPLANATION

—— 80.0 —— WATER-TABLE CONTOUR--Shows relative altitude of water table. Contour interval (a) 0.5 foot; (b) 1 foot. Top of casing altitude at injection well is assumed to be 100 feet; altitudes at other wells are referred to this datum

(6-11)$_o$ INJECTION WELL

(6-4)$_\bullet$ OBSERVATION WELL

Figure 12. Water-table configuration at the site near burial ground 6 for (a) July 12, 1977 and (b) January 23, 1978.

Table 6. Difference in water-level altitudes between injection well 6-11 and observation wells

[Values are in feet. Minus sign indicates that water-surface altitude in observation well was greater than that of injection well; –, measurement not made. Rainfall data were recorded at gage in burial ground 6, except values with an asterisk, which were recorded at gage in burial ground 5 (Webster and others, 1982)]

	Observation well							
Date	6-10	6-9	6-8	6-7	6-6	6-5	6-4	Remarks
7-12-77	0.36	0.08	0.74	0.83	0.77	0.82	0.80	Measurement made 2 days before injection.
11-09-77	0.22	–	–	–	–	–	1.01	
12-05-77	1.59	.07	3.19	3.71	3.70	3.51	3.37	0.97 inch of rain on 12-04 and 12-05.
12-19-77	1.69	.32	2.68	3.11	3.10	2.98	2.90	
1-03-78	1.47	.23	2.37	2.75	2.78	2.63	2.57	
1-18-78	1.35	.07	2.27	2.67	2.77	2.61	2.55	0.90 inch of rain on 1-17 and 1-18.
1-23-78	1.38	.12	2.58	3.02	3.06	2.86	2.77	
1-30-78	1.03	.54	2.48	3.13	3.07	2.86	2.75	1.89 inches of rain from 1-24 through 1-27.
2-13-78	1.43	.21	2.30	2.76	2.75	2.57	2.51	
2-27-78	.93	.03	1.57	1.89	1.97	1.74	1.74	
3-13-78	.75	-.15	1.78	2.16	2.10	2.02	1.95	1.87 inches of rain from 3-08 through 3-10.
3-27-78	1.29	.16	2.09	2.52	2.45	2.34	2.28	
4-10-78	.89	.02	1.51	1.83	1.77	1.68	1.63	
4-24-78	.63	.07	1.10	1.36	1.20	1.17	1.25	
5-10-78	.23	.26	1.06	1.34	1.33	1.25	1.20	0.95 inch of rain on 5-08.
5-22-78	.87	.06	1.57	1.88	1.80	1.74	1.69	
6-05-78	.67	-.04	1.17	1.46	1.38	1.33	1.27	1.20 inches of rain on 6-02.
6-19-78	.93	.05	1.59	1.90	1.81	1.72	1.71	
7-03-78	.70	-.06	1.17	1.38	1.36	.99	1.29	
7-17-78	.45	-.86	.79	.85	.94	.87	.84	2.91 inches of rain on 7-15 through 7-16.
7-31-78	.40	-.08	.73	.78	.85	.79	.78	
8-14-78	.39	-.43	.62	.59	.58	.62	.59	4.95 inches of rain from 8-04 through 8-14.
8-28-78	.59	-.11	.93	1.14	.99	1.02	1.02	0.94 inch of rain on 8-25 and 8-26.
9-11-78	.77	.21	1.09	1.26	1.15	1.13	1.13	1.23 inches of rain on 9-10 and 9-11.
9-25-78	.39	-.12	.67	.83	.74	.74	.72	
10-11-78	.33	-.08	.60	.75	.68	.61	.64	
10-30-78	.28	-.07	.46	.64	.60	.57	.55	
11-13-78	.22	-.07	.43	.55	.53	.49	.47	
11-27-78	.12	-.05	.36	.46	.47	.41	.38	1.29 inches of rain from 11-22 through 11-24.
12-11-78	.30	-.43	1.62	1.00	.78	.92	.88	2.19 inches of rain on 12-04 through 12-05. 2.15 inches of rain from 12-08 through 12-09.
12-27-78	1.05	-.03	1.60	1.92	1.66	1.73	1.72	
1-11-79	2.15	.36	3.35	3.96	3.65	3.71	3.62	2.03 inches of rain on 1-06 and 1-07.
1-22-79	2.01	-.28	3.47	4.14	3.76	3.97	3.08	2.45 inches of rain from 1-19 through 1-22.
2-06-79	1.79	.34	2.68	3.10	3.02	3.00	2.93	
3-05-79	2.55	-.02	4.36	5.09	4.75	6.00	4.91	*2.35 inches of rain on 3-03 and 3-04.
3-26-79	1.43	.13	2.23	2.64	2.51	2.51	2.46	*1.07 inches of rain on 3-23 and 3-24.
4-09-79	1.18	.10	2.04	2.42	2.24	2.28	2.23	
4-23-79	1.49	.33	2.43	2.88	2.71	2.70	2.63	
5-07-79	1.00	.11	1.67	1.96	1.83	1.87	1.82	1.39 inches of rain on 5-03 and 5-04.
5-21-79	.70	.03	1.22	1.47	1.32	1.38	1.35	1.16 inches of rain on 5-20 and 5-21.
6-05-79	1.28	.26	2.40	2.82	2.55	2.71	2.68	4.03 inches of rain from 5-31 through 6-03.
6-19-79	1.42	.24	2.18	2.57	2.41	2.42	2.37	
7-03-79	.89	.01	1.46	1.73	1.59	1.62	1.60	
7-16-79	.22	-.25	.86	1.06	1.04	.99	.94	4.72 inches of rain from 7-07 through 7-15.
5-27-80	.46	-.12	.91	1.10	.86	1.01	.99	
5-26-81	.43	-.08	.65	.66	.43	.68	.67	

factor governing flow direction in the underlying bedrock of this area, the role of those openings as being the principal conduits of flow in the regolith at the study sites has been greatly reduced. If this were not so, the largest concentrations of tracer would have been detected in samples from the wells numbered -4, -5, -9, and -10 at each site, and only small concentrations, if any at all, would have been detected in the samples from wells 4-7 and 6-7.

Although the largest concentrations of tritium were detected in water from wells normal to strike, substantial concentrations were also detected in some of the other wells, reflecting the influence of bedding planes on flow direction, and indicating that a lateral component of flow also occurred. Bedding-plane influence perhaps is shown best in the graph for well 4-9 (figs. 6 and 7), located sub-parallel to strike from the injection well. After breakthrough, the tritium concentration rose rapidly and peaked first within 12 days, faster than at any other well. Several peaks, some with higher values, occurred later, and each one, like the first one, correlates with an occurrence of substantial rain. Infiltration appears to have driven the tritiated water in pulses through a pathway having greater hydraulic conductivity along the bedding than across it. Such a pathway could likely be a linear opening between beds that began development as a bedding-plane fracture before the rock had weathered to regolith. The graphs for wells 4-10 and 6-4 also suggest bedding-plane influence, but the relation is less apparent because of the smaller concentrations.

Contour maps of the concentration data provide a different perspective for observing the principal directions of flow and development of the plumes. A map for the site near burial ground 4, 9 days after injection (fig. 13a), shows the leading edge of a developing plume moving primarily southeast across the beds past well 4-7, following the direction of the water-table gradient. By the 57th day (September 8, 1977), the plume had spread beyond that well and was also expanding laterally along strike, probably following relict bedding-plane openings (fig. 13b). By the 100th day (October 21, 1977), the plume had been detected in six of the seven observation wells, and its leading edge had spread in most directions considerably beyond the perimeter of the well field (fig. 13c).

A map for the burial ground 6 site for November 9, 1977, 118 days after injection and shortly after tritium was first detected in one of the observation wells, shows that the plume was spreading across the beds at a small angle to the inferred water-table gradient (fig. 14a). By the 158th day (December 19, 1977), it had widened and had been detected also at well 6-7, generally in line with the water-table gradient, and at well 6-4, along strike from the injection well (fig. 14b). By the 200th day (January 30, 1978), the plume had reached all of the wells from northeast to south except well 6-6 (fig. 14c). Its absence at this point probably indicates that fractures in the saturated regolith beds surrounding this well were not in direct hydraulic continuity with the network of openings through which the plume was spreading.

The contour maps also show that the plumes spread northwest from the two injection wells, opposite the direction of the water-table gradient, for an indefinite distance. This becomes evident if the contours are to close efficiently.

These maps show that even though the principal direction of flow was across the beds, a significant secondary component of flow occurred parallel to them. The large degree of lateral spreading of the plume is consistent with a conceptual model of an anisotropic ground-water system that has greater hydraulic conductivity parallel to strike than across it. The many short-term variations in water-table direction and gradient likely could have been a factor contributing to the lateral spread of the plumes.

Matrix Diffusion

The leading edge of the tritium plume moved moderately fast (burial ground 6 site) to very fast (site near burial ground 4), but the bulk of the tritium mass at each site was transported at a much slower velocity. Figures 7 and 10, respectively, show that about 2 years elapsed before much of the mass had passed well 4-7, 12 feet down-gradient from the injection well, and as much as 3 years at well 6-7, 30 feet down-gradient from the other injection well. Contour maps for both well fields nearly 5 years after injection—necessarily generalized because of the lack of monitoring wells outside of each site—show that even though concentrations had declined, large residual concentrations remained (figs. 13d and 14d). They further show that the centers of mass of the plumes probably had not moved beyond the well fields.

The long periods of time involved seem to indicate that a natural process was operating to retard the transport of tritium through the saturated regolith. The exchange of tritiated water molecules with the bound

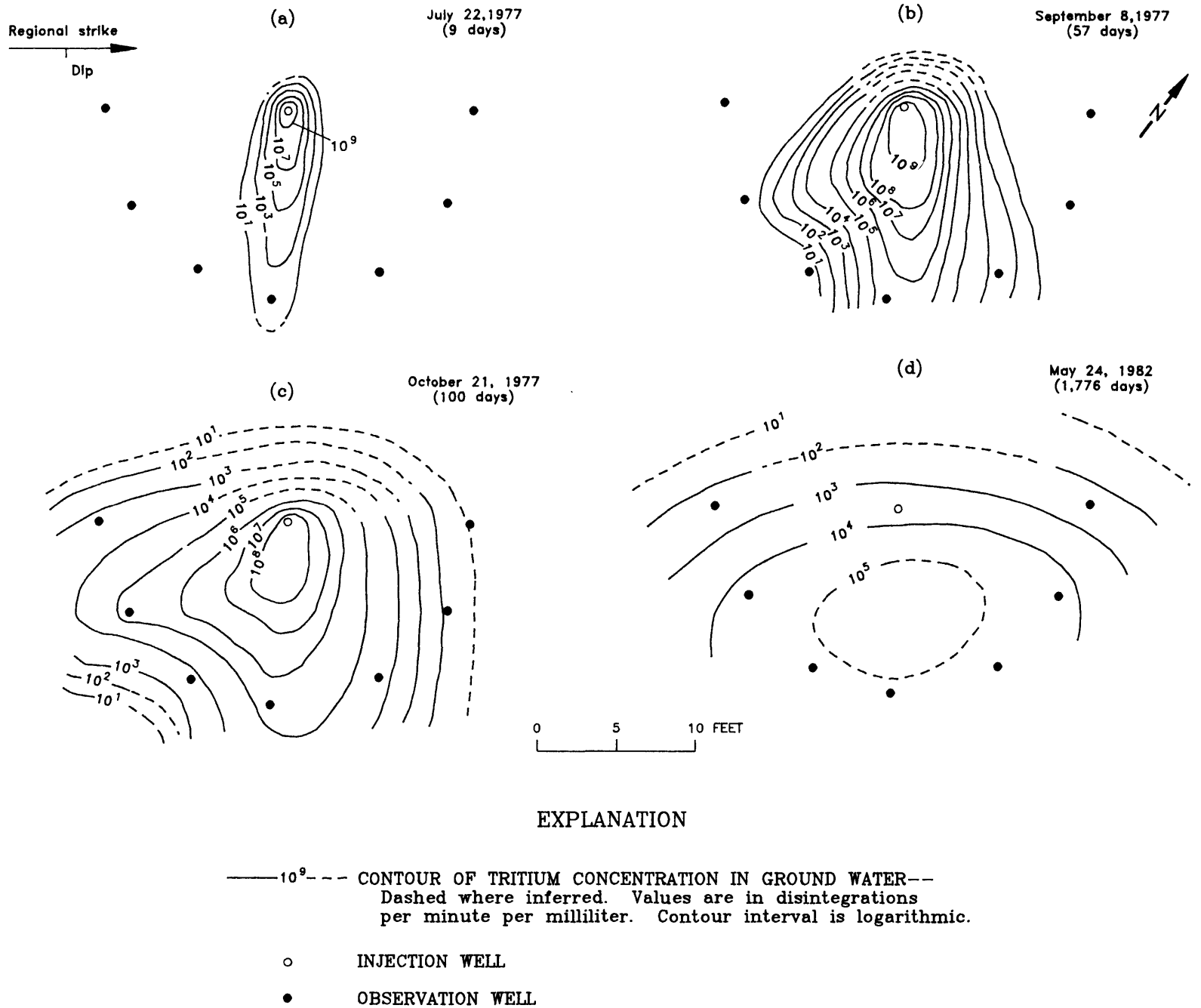


Figure 13. Contours of tritium concentration for site near burial ground 4 (a) 9 days, (b) 57 days, (c) 100 days, (d) 1,776 days after tracer introduction.

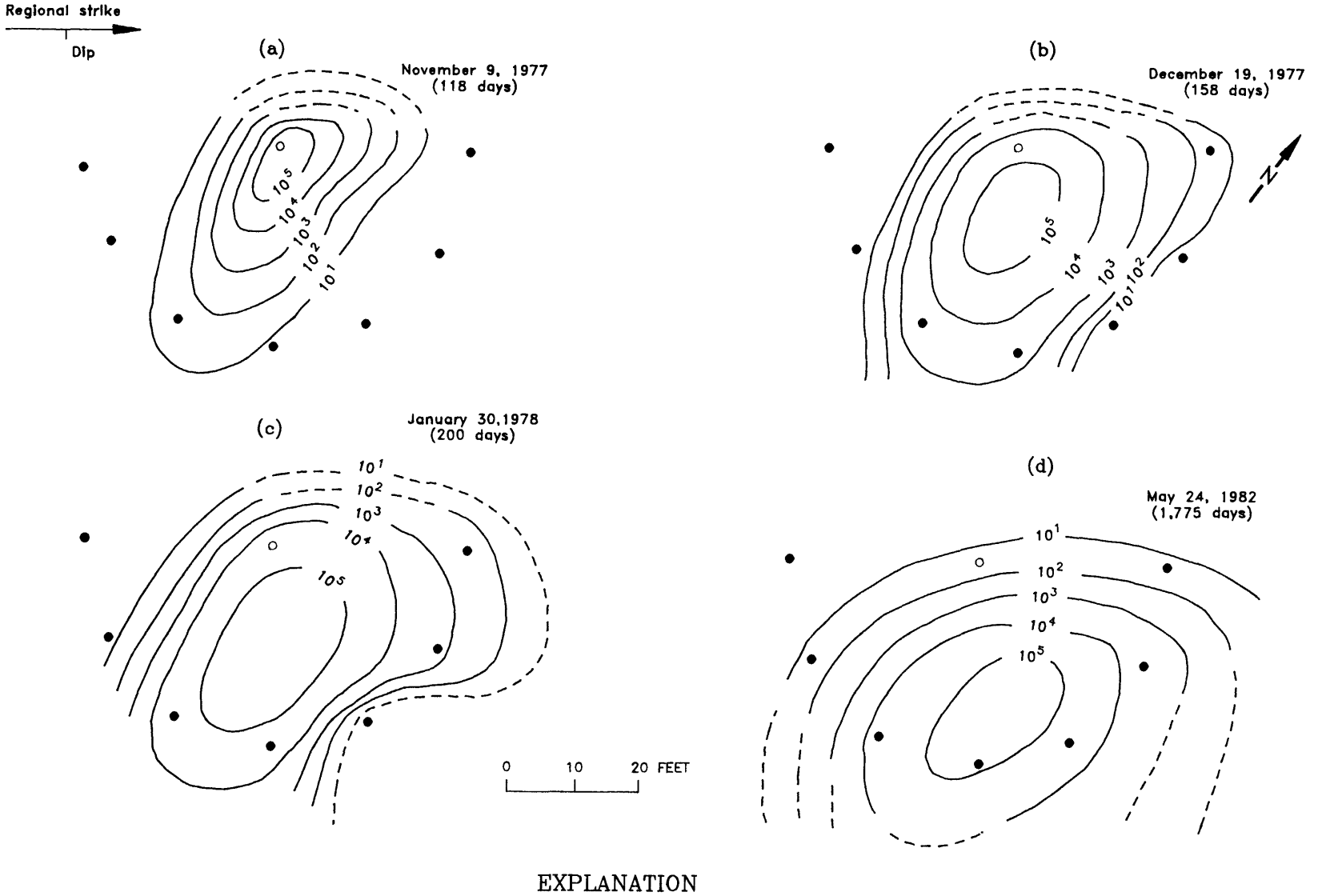


Figure 14. Contours of tritium concentration for site in burial ground 6 (a) 118 days, (b) 158 days, (c) 200 days, and (d) 1,775 days after tracer introduction.

water of soil and ion exchange reactions with clays may have contributed to retardation, as suggested by studies previously referenced, but it appears that matrix diffusion also could have played a significant and perhaps much larger role. By this process, solutes in ground water flowing through fractures diffuse to pore water of the aquifer matrix and diffuse back to ground water flowing through the fractures after the concentration gradient reverses (Freeze and Cherry, 1979; Grisak and Pickens, 1980). In effect, pore water in the aquifer matrix can become a storage medium for a dissolved contaminant in ground water. Later, after the concentration in flowing ground water becomes less than that of the pore water, the matrix water becomes a secondary source of the contaminant as the contaminant diffuses back to ground water. The net effect of the process is to retard contaminant transport.

Matrix diffusion has not received wide recognition, probably because its role in the transport of solutes has been recognized only recently. Foster (1975) was the first to apply the concept to contaminant transport in water, suggesting that it could explain the behavior of water-borne tritium in unsaturated fractured chalk in England. Later applications have included evaluations of contaminant transport and ground-water tracer transport through fractures in clay-rich till in Canada (Day, 1977; Pankow and others, 1986; McKay and others, 1993a, 1993b), and clay in Mexico (Rudolph and others, 1991). Laboratory and simulation studies have also shown the viability of the process in crystalline rock (Bradbury and Green, 1986; Alexander and others, 1990) and in fractured, porous rock (Feenstra and others, 1984; Tomasko, 1986). Recently, the continued transport of tritium through fractures at shallow depth from ORNL's burial ground 5, which has not received new sources of this radionuclide in more than 20 years, has been attributed to this process (Wickliff and others, 1991).

At injection well 4-11, the observed loss in tritium activity during 5 years was seven orders of magnitude. To examine the possibility that matrix diffusion may have contributed to this decline, concentration data for that well were incorporated into a simple model that simulates the process. Results indicated that if the well bore did not intercept any fractures and if the ground-water system was static, the initial concentration of tritium would be reduced by about one order of magnitude during a 5-year period as a result of radioactive decay and diffusion of tritium into pore water of the regolith surrounding the well. If the tracer entered a blind fracture of 2 mm width, the concentration in that fracture would be reduced three to four orders of magnitude during the 5-year period by these two processes. If the tracer entered smaller aperture fractures, even greater losses in concentration would occur (W.W. Wood, U.S. Geological Survey, oral commun., 1995). Although the simulation does not provide proof that matrix diffusion did occur, the model results are generally consistent with the observed data, which implies that tracer transport at the sites may have been affected by this process.

The potential for the process to reduce tritium mobility was not recognized at the time the tracer tests were conducted. Considering that tritium had been described in the literature as a highly conservative tracer, the length of time for the tritium plume to pass the observation wells was longer than expected and became a matter of concern. In an effort to shorten the tests, a feasibility experiment for this purpose was conducted at the site near burial ground 4, the results of which also are consistent with effects of this process. On March 10, 1978, 7 months after the tests were started, a carboy of water was pumped from well 188, located in an uncontaminated area about 300 feet northeast of and on the same hillside as the test site. After adding fluorescein dye to the water, the dyed water was tremied to the bottom of injection well 4-11 while the overlying, clear, tritiated water in the well (containing an estimated 2.7×10^{-2} curie of activity) was evacuated and placed in another carboy. Analysis of a water sample collected the next day showed that the initial concentration (6.23×10^{6} dpm/mL) had been reduced by about 40 percent (3.81×10^{6} dpm/mL). On March 14, the water in well 4-11 was again removed and replaced with non-tritiated water from well 188, this time undyed. Tritium activity in a sample collected 3 days later was 2.33×10^{6} dpm/mL. The procedure was repeated on March 28 and again on April 6. The concentration on April 7 was 2.80×10^{5} dpm/mL. On that date the procedure was repeated four times, and analysis of a sample collected 3 days later showed that the concentration had more than doubled to 6.42×10^{5} dpm/mL. By May 10—no additional evacuations had been performed—the concentration had nearly quadrupled again to 2.15×10^{6} dpm/mL and was at nearly the same level as it would have been if the experiment had not been performed (fig. 8).

The large concentrations of tritium measured in the well water following each flushing are explainable by matrix diffusion. After releasing the tracer in well

4-11, some of the tritium diffused into pore water of the matrix near the well, and that matrix was now supplying stored tritium by outward diffusion to recharge entering the area and to the fresh water placed in the well.

A similar feasibility test was not performed at the well field in burial ground 6. However, the storage potential for tritium or other nonreactive contaminants by this process in the regolith of the Nolichucky Shale of that site appears to be less than that of the Pumpkin Valley Shale of the site near burial ground 4. This is evident from the steeper slope of the curves shown in figure 8 for the first few months of the tests and the sustained lower concentrations of tritium in water from the injection wells during the remainder of the period of record. Lower storage potential at the test site in burial ground 6 probably results from the beds of the saturated regolith being less weathered, which gives them less porosity and a smaller volume of water held in the matrix.

The results of these tests imply that the transport of contaminants in ground water in Melton Valley could be significantly affected by matrix diffusion. The process also could have important implications regarding aquifer remediation, particularly by the commonly used method known as "pump and treat." Simply pumping a well in jointed or fractured fine-grained regolith for the purpose of removing ground water contaminated with tritium or some other nonreactive substance might provide only minor benefit. It appears that pumping would quickly remove water from joints and other secondary openings, but would remove only a negligible amount of the contaminated interstitial or pore water. The contaminant stored in the matrix water would then continue to diffuse outward to the recharge flowing through the secondary openings as long as a concentration gradient existed. This and other implications of matrix diffusion as it relates to aquifer remediation have been summarized by Wickliff and others (1991) and Solomon and others (1992a).

Comparison to Results of Other Ground-Water Tracer Tests

Ground-water tracer tests have been used in some of the earlier hydrogeologic studies of Melton Valley to help define ground-water flow and hence, probable contaminant flow paths. A few tests that relate to ground-water flow in the regolith are summarized here to show the variability in results and, consequently, the difficulty in defining flow in a medium as stratigraphically and structurally complex as the Conasauga Group.

In 1954, a test was conducted at a site located nearly 1,000 feet west-northwest of the burial ground 6 test site in an area recently mapped as having the carbonate-rich (Haase and others, 1985), lowermost beds of the Nolichucky Shale (Hatcher and others, 1992). A uranyl nitrate solution was introduced to a cone-shaped pit 30 feet in diameter and 5 feet deep, and the path of nitrate travel was monitored with two rings of augered wells, 12 to 19 feet deep, surrounding the pit. That hard rock was present in the shallow subsurface is evidenced by having to offset the planned locations of some of the wells. Contours of nitrate concentrations in the well water indicated that the tracer flowed in a direction about 30° from strike (Morton, 1955). It is inferred from water-level data for the area, collected two decades later (Webster and others, 1980), that the direction of flow probably was also at an angle to the water-table gradient. The results of this test indicated that beds resistant to weathering are present in the regolith of this area and to some degree still influence the direction of shallow ground-water flow.

During the early 1980's, a ground-water tracer test was included in the study of an area about 300 feet west of the conical pit used in the earlier test. The area is only slightly lower in the stratigraphic section and falls approximately along the contact between the Nolichucky Shale and the Maryville Limestone (Hatcher and others, 1992). After injecting a homologous series of chlorofluorocarbons as a tracer, Vaughn and others (1982) reported that the largest concentrations were carried to those wells that lie in a direction generally parallel to strike, which differed considerably from the direction of the water-table gradient as inferred from water-level measurements in wells of that area. They theorized that flow occurred relatively rapidly through fractures, basing their conclusion on the attenuated arrival pattern of the tracer, an oval-shaped drawdown pattern upon a later aquifer test, discovery of two anticlines in the subsurface after excavating nine shallow trenches, and projection to this area of a strike-joint set associated with the Pumpkin Valley Shale. Their work showed that the direction of ground-water flow at this study site is still strongly influenced by gradients within the underlying

structural features rather than by the apparent water-table gradient.

During the early 1960's, a tracer test was conducted near pits 2 and 3 which had been used earlier for the disposal of liquid wastes. The pits were located about halfway between the two test sites of this report and are underlain by the Maryville Limestone. Twenty-one curies of tritium dissolved in water were introduced to five 40-foot deep wells, spaced about 1-1/2 feet apart, and located along a line approximately normal to strike. The direction of the water-table gradient was not reported but, considering the location, probably differed by at least 30° from strike, and beyond the immediate area of the injection wells, that direction probably was under-represented by monitoring wells. After monitoring several wells for 6 months, the investigators determined that the tritiated water had moved southwesterly (in the general direction of strike) at a modal velocity of about 0.5 foot per day to a distance of 10 feet, but they were not able to track the tracer with certainty beyond that, attributing the difficulty to dilution, diffusion, and other factors (Lomenick and Gera, 1964; Lomenick and others, 1964). They did note, however, that at the few wells where the tracer was detected, concentrations declined at a much slower rate than they built up, which implies that matrix diffusion could have played a role in this test also.

In 1976, a doctoral candidate investigating halocarbons as potential ground-water tracers used the well field in burial ground 6 as a test site before its use for the tritiated-water test described in this report. He added 23 milligrams of dibromodifluoromethane, a highly volatile compound, mixed with 5 mL of ethanol and 1 liter of water, to the water in well 6-11. An additional 4 liters of water were poured through the injection tubing to flush the tubing and force the tracer into the aquifer. (The 5 liters of fluid would have raised the water level by about 2 feet and temporarily imparted an unnatural gradient.) Samples were collected weekly from the end of the second week through the ninth week and analyzed elsewhere. The largest concentration (0.40 part per trillion) was detected in the well 6-6 sample 3 weeks after injection, after which the concentration declined quickly. Smaller concentrations were detected in adjacent wells 6-5 and 6-7, and trace concentrations were detected in other observation wells. By the end of the fifth week, all but a residual concentration (1 to 2 parts per trillion) had left the injection well (Tamura and others, 1980). His results differed greatly, both in time of travel and behavior of the tracer, from the results presented in this report for the same site.

The differences in the test results reflect the variability of stratigraphy and structure within the Melton Valley waste-disposal area, differences in extent of weathering of beds in the regolith, differences in the design and execution of the tests, and other factors. The two tests described in detail in this report have demonstrated that at the sites tested, regolith beds of the Conasauga Group are sufficiently weathered to permit significant flow to cross them, and that at these sites the principal direction of ground-water flow corresponds generally to the direction of the water-table gradient. Because of the small areas involved in the tests and the areal variability of this geologic unit, however, the results of these tests, or the results of any other limited area tracer test, should be used with caution if applied to large areas of the valley.

SUMMARY

Ground-water tracer tests were conducted in the regolith at a site near burial ground 4 and a site in burial ground 6 before that waste-disposal area had undergone substantial development. The sites are underlain by the Pumpkin Valley Shale and the Nolichucky Shale, respectively, of the Conasauga Group of Cambrian age. The purpose of the tests was to determine if rock weathering in the regolith had progressed sufficiently to permit water to flow through joints that had developed in the beds, that is, in a direction transverse to the bedding and formation strike.

To examine this hypothesis, at each site seven shallow observation wells were constructed in a semicircle around an injection well at the center. A line through the injection well and the two observation wells at the ends of each array was parallel to strike, and a line through the injection well and center observation well was normal to strike and generally parallel to the maximum water-table gradient. The radii of the semi-circles were 12 feet and 30 feet.

About 50 curies of tritium dissolved in water were added to the water of the injection well near burial ground 4, and about 100 curies to the injection well in burial ground 6. Initial concentrations were 2.06×10^{10} dpm/mL and 1.46×10^{10} dpm/mL, respectively. Samples for tritium analyses were

collected from all wells frequently for 2 years and after that, once annually for 3 years.

Tritium was detected in samples from all of the observation wells. The length of time for sustained concentrations to be detected ranged from 9 days or less to 205 days at the site near burial ground 4, and from 112 to 265 days at the burial ground 6 site. Concentrations in the observation wells ranged from 8.82×10^6 dpm/mL to less than the level of detection, which varied from ≤6 to 96 dpm/mL.

At each site, the largest concentrations of tracer in the observation wells were detected in samples from the well normal to strike and generally in line with the maximum water-table gradient. Much smaller concentrations were measured in samples from the wells oriented parallel to strike and which had shallow hydraulic gradients from the injection well. The results demonstrated that at the two sites tested, regolith beds have weathered sufficiently to permit water to flow through joints and other openings that have developed in them, and that the direction of the water-table gradient is the primary factor governing the direction of ground-water flow rather than the orientation of bedding-plane openings and hydraulic gradients along those openings. Nevertheless, the influence of bedding-plane openings upon flow direction, important in the deeper rock, has not been eliminated. At each site, large concentrations of tritium were also detected in water from at least one well sub-parallel to strike, and concentration-contour maps for these sites show that the plumes not only moved down-gradient but spread laterally as they developed, indicative of a significant secondary component of flow along bedding planes.

Matrix diffusion may have played an important role in these tests by acting as a mechanism for retarding transport. Evidence for the process includes the length of time that large concentrations of tracer were detected at many of the observation wells, the persistence of residual concentrations at the injection wells and the observation wells, the relatively rapid movement of the leading edge of the plumes but very slow movement of the centers of mass, and the reoccurrence of large concentrations of tritium in water of one of the injection wells shortly after each of several flushings. The general conformance of observed concentration data with the results of a matrix-diffusion simulation model for one of the injection wells shows that the observed data are consistent with the effects of matrix diffusion. The tracer-test results further show that quick remediation of an aquifer composed of jointed or fractured regolith with high silt and clay content probably would be difficult by the "pump and treat" method. Pumping would quickly remove contaminated water from joints and fractures, but only slowly remove contaminated water from the interstices or pores of the fine-grained material.

The results of these tests differ from the results of previous ground-water tracer tests conducted in the regolith in the waste-disposal area. Because of the small areas involved in all of the tests and the areal variability of the Conasauga Group, the results of any limited area tracer test in this unit should be used with caution if applied to large areas of the valley.

SELECTED REFERENCES

Alexander, W.R., McKinley, I.G., MacKenzie, A.B., and Scott, R.D., 1990, Verification of matrix diffusion by means of natural decay series disequilibria in a profile across a water-conducting fracture in granitic rock, *in* Oversby, V.M., and Brown, P.W., eds., International symposium on the scientific basis for nuclear waste management, 13th, Boston, Massachusetts, 1989 [Proceedings], p. 567-576.

Ames, L.L, and Rai, Dhanpat, 1978, Radionuclide interactions with soil and rock media, v. 1: U.S. Environmental Protection Agency, EPA 520/6-78-007, 307 p.

Barnett, John, 1954, Geological investigations, waste disposal area, Oak Ridge National Laboratory, Oak Ridge, Tennessee: Mariemont, Ohio, U.S. Army Corps of Engineers, Ohio River Division Laboratories, 6 p., 2 maps.

Bradbury, M.H., and Green, A., 1986, Investigations into the factors influencing long range matrix diffusion rates and pore space accessibility at depth in granite: Journal of Hydrology, v. 89, p. 123-139.

Cowser, K.E., and Parker, F.L., 1958, Soil disposal of radioactive wastes at ORNL: criteria and techniques of site selection and monitoring: Health Physics, v. 1, p. 152-163.

Day, M.J., 1977, Analysis of movement and hydrochemistry of ground water in the fractured clay and till deposits of the Winnipeg area, Manitoba: Waterloo, Ontario, Canada, University of Waterloo, unpublished M.Sc. thesis, 210 p.

deLaguna, Wallace, 1956, Some geologic factors that influence disposal of radioactive wastes into pits, *in* Seminar on sanitary engineering aspects of the Atomic Energy Industry, Cincinnati, 1955: U.S. Atomic Energy Commission, Division of Technical Information (Report) TID-7517, part 1b, p. 426-456.

Feenstra, Stan, Cherry, J.A., Sudicky, E.A., and Haq, Zia, 1984, Matrix diffusion effects on contaminant migration from an injection well in fractured sandstone: Ground Water, v. 22, no. 3, p. 307-316.

Foster, S.S.D., 1975, The chalk groundwater tritium anomaly—a possible explanation: Journal of Hydrology, v. 25, p. 159-165.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Grisak, G.E., and Pickens, J.F., 1980, Solute transport through fractured media, 1: the effect of matrix diffusion: Water Resources Research, v. 16, no. 4, p. 719-730.

Haase, C.S., and Vaughn, N.D., 1981, Stratigraphy and lithology of the Conasauga Group in the vicinity of Oak Ridge, Tennessee: Geological Society of America abstracts with programs, Boulder, Colo., v. 13, no. 1, p. 8.

Haase, C.S., Walls, E.C., and Farmer, C.D., 1985, Stratigraphic and structural data for the Conasauga Group and the Rome Formation on the Copper Creek fault block near Oak Ridge, Tennessee: Preliminary results from test borehole ORNL-Joy No. 2: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-9159, 88 p.

Hatcher, R.D., Jr., Lemiszki, P.J., Dreier, R.B., Ketelle, R.H., Lee, R.R., Leitzke, D.A., McMaster, W.M., Foreman, J.L., and Lee, S.Y., 1992, Status report on the geology of the Oak Ridge Reservation: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-12074, 244 p., 1 pl.

Jacobs, D.G., 1968, Sources of tritium and its behavior upon release to the environment: U.S. Atomic Energy Commission, AEC Critical Review Series.

———1974, Impacts in groundwater of effluents arising in the nuclear industry, *in* Environmental analysis and environmental monitoring for nuclear power generation, Lecture notes, Continuing education in engineering, Paper 16: Berkeley, University of California, 8 p.

Kaufman, W.J., and Orlob, G.T., 1956a, An evaluation of ground-water tracers: Transactions, American Geophysical Union, v. 37, no. 3, p. 297-306.

———1956b, Measuring ground water movement with radioactive and chemical tracers: Journal American Water Works Association, v. 48, p. 559-572.

Lomenick, T.J., and Gera, F., 1964, Evaluation of fission-product distribution and movement in and around chemical waste seepage pits 2 and 3, *in* Waste treatment and disposal quarterly progress report, November 1963-January 1964: U.S. Atomic Energy Commission, Oak Ridge National Laboratory (Report) ORNL/TM-830, p. 120-125.

Lomenick, T.J., Gera, Ferrucio, and Wyrick, H.J., 1964, Evaluation of fission product distribution and movement in and around chemical waste seepage pits 2 and 3, *in* Health Physics Division annual progress report for period ending July 31, 1964: U.S. Atomic Energy Commission, Oak Ridge National Laboratory (Report) ORNL-3697, p. 43-45.

Lomenick, T.J., and Wyrick, H.J., 1965, Geohydrological evaluation of solid waste storage area 6: U.S. Atomic Energy Commission, Oak Ridge National Laboratory (Report) ORNL-TM-1327, 17 p.

McKay, L.D., Cherry, J.A., Bales, R.C., Yahya, M.T., and Gerba, C.P., 1993b, A field example of bacteriophage as tracers of fracture flow: Environmental Science & Technology, v. 27, no. 6, p. 1075-1079.

McKay, L.D., Gillham, R.W., and Cherry, J.A., 1993a, Field experiments in a fractured clay till, 2: Solute and colloid transport: Water Resources Research, v. 29, no. 12, p. 3879-3890.

Moore, G.K., 1988, Concepts of groundwater occurrence and flow near Oak Ridge National Laboratory, Tennessee: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-10969, 96 p.

———1989, Groundwater parameters and flow systems near Oak Ridge National Laboratory: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-11368, 83 p.

Morton, R.J., 1955, Radioactive waste disposal, *in* Health Physics Division semiannual progress report for period ending July 31, 1954: U.S. Atomic Energy Commission, Oak Ridge National Laboratory (Report) ORNL-1763, p. 14-17.

Pankow, J.F., Johnson, R.L., Hewetson, J.P., and Cherry, J.A., 1986, An evaluation of contaminant migration patterns at two waste disposal sites on fractured porous media in terms of the equivalent porous medium (EPM) model: Journal of Contaminant Hydrology, v. 1, p. 65-76.

Rudolph, D.L., Cherry, J.A., and Farvolden, R.N., 1991, Groundwater flow and solute transport in fractured lacustrine clay near Mexico City: Water Resources Research, v. 27, no. 9, p. 2187-2201.

Sledz, J.J., and Huff, D.D., 1981, Computer model for determining fracture porosity in the Conasauga Group, Oak Ridge National Laboratory, Tennessee: [U.S.] Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-7695, 138 p.

Solomon, D.K., Moore, G.K., Toran, L.E., Dreier, R.B., and McMaster, W.M., 1992a, Status report, a hydrologic framework for the Oak Ridge Reservation: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-12026, variously paginated.

Solomon, D.K., Moore, G.K., Toran, L.E., Dreier, R.B., McMaster, W.M., and Huff, D.D., 1992b, The hydrology of the Oak Ridge Reservation—a conceptual model, *in* Extended abstracts from fifth Tennessee water resources symposium: Nashville, Tennessee

section of the American Water Resources Association, p. 12-14.

Stewart, G.L., and Stetson,J.R., 1975, Tritium and deuterium as water tracers in hydrologic systems: Amherst, University of Massachusetts Water Resources Research Center, Publication no. 55, 44 p.

Tamura, T., Eyman, L.D., Stueber, A.M., and Ward, D.S., 1980, Progress report of disposal area studies at Oak Ridge National Laboratory: period of October 1, 1975 to September 30, 1977: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL-5514, 83 p.

Tomasko, David, 1986, The effects of a bimodal pore distribution on matrix diffusion in a fractured porous medium: U.S. Department of Energy, Sandia National Laboratories (Report) SAND87-0265, 28 p.

Tucci, Patrick, 1992, Hydrology of Melton Valley at Oak Ridge National Laboratory: U.S. Geological Survey Water-Resources Investigations Report 92-4131, 76 p.

Vaughn, N.D., Haase, C.S., Huff, D.D., Lee, S.Y., and Walls, E.C., 1982, Field demonstration of improved shallow land burial practices for low-level radioactive solid wastes: preliminary site characterization and progress report: [U.S.] Department of Energy, Oak Ridge National Laboratory (Report) ORNL/TM-8477, 112 p.

Webster, D.A., Beatty, J.S., Benjamin, P.M., and Tranum, W.M., 1980, Water-level data for wells in burial ground 6, Oak Ridge National Laboratory, Tennessee, 1975-1979: U.S. Geological Survey Open-File Report 81-57, 100 p.

———1982, Precipitation data for burial grounds 5 and 6, Oak Ridge National Laboratory, Tennessee, 1976-1980: U.S Geological Survey Open-File Report 82-254, 15 p.

Webster, D.A., and Bradley, M.B., 1988, Hydrology of the Melton Valley radioactive-waste burial grounds at Oak Ridge National Laboratory, Tennessee: U.S. Geological Survey Open-File Report 87-686, 115 p.

Wickliff, D.S., Solomon, D.K., and Farrow, N.D., 1991, Preliminary investigation of processes that affect source term identification: U.S. Department of Energy, Oak Ridge National Laboratory (Report) ORNL/ER-59, 31 p.

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APPENDIXES

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM

[Results are in disintegrations per minute per milliliter of sample. E is exponent to the base 10. Values are unadjusted for radioactive decay. Analyses were performed by Hugh Parker, Analytical Chemistry Division, Oak Ridge National Laboratory, Tennessee. Dates are given by year, month, and day (yymmdd); ≤, equal to or less than; --, no sample collected]

Site near burial ground 4

Date	Well number							
yymmdd	4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
770703	≤6	≤6	≤6	≤6	≤6	≤6	≤6	≤6
770713	5.27 E2	9.88 E2	4.29 E2	3.63 E2	8.07 E2	2.74 E3	1.22 E3	8.19 E2
770713	--	--	--	--	--	--	--	2.06 E10
770716	1.04 E3	1.36 E3	1.34 E3	6.43 E3	7.53 E2	2.56 E3	6.73 E2	--
770719	1.53 E2	1.58 E2	1.62 E2	1.22 E2	1.79 E2	1.12 E2	7.8 E4	--
770722	≤6	≤6	≤6	1.21 E2	≤6	≤6	≤6	--
770725	≤6	≤6	≤6	1.43 E3	≤6	≤6	≤6	--
770728	≤6	≤6	≤6	7.18 E3	≤6	≤6	≤6	--
770731	≤6	≤6	≤6	2.06 E4	≤6	≤6	≤6	--
770803	≤6	≤6	≤6	3.95 E4	≤6	≤6	≤6	--
770806	≤6	≤6	≤6	5.56 E4	≤6	≤6	≤6	--
770809	≤6	≤6	≤6	8.41 E4	≤6	≤6	≤6	--
770812	≤6	≤6	≤6	1.14 E5	≤6	≤6	≤6	--
770814	≤6	≤6	≤6	1.51 E5	≤6	≤6	≤6	--
770816	≤6	≤6	≤6	1.69 E5	≤6	≤6	≤6	--
770817	≤6	≤6	≤6	2.01 E5	≤6	≤6	≤6	--
770818	≤6	≤6	≤6	2.10 E5	≤6	≤6	≤6	--
770819	≤6	≤6	≤6	2.18 E5	≤6	≤6	≤6	--
770820	≤6	≤6	≤6	2.07 E5	≤6	≤6	≤6	--
770821	--	--	--	2.66 E5	--	--	--	--
770823	≤6	≤6	≤6	2.73 E5	≤6	≤6	≤6	--
770824	≤6	≤6	≤6	3.42 E5	≤6	≤6	≤6	--
770825	≤6	≤6	≤6	3.42 E5	≤6	≤6	≤6	--
770826	≤6	≤6	≤6	3.85 E5	≤6	≤6	≤6	--
770827	≤6	≤6	≤6	3.86 E5	≤6	≤6	≤6	--
770828	≤6	≤6	≤6	4.23 E5	≤6	≤6	≤6	--
770829	≤6	≤6	≤6	4.50 E5	≤6	≤6	≤6	--
770830	≤6	≤6	≤6	4.48 E5	≤6	≤6	≤6	--
770831	≤6	≤6	≤6	4.52 E5	≤6	≤6	≤6	--
770901	≤6	≤6	≤6	4.70 E5	≤6	≤6	≤6	--
770902	≤6	≤6	≤6	4.68 E5	≤6	≤6	≤6	--
770903	≤6	≤6	≤6	4.83 E5	≤6	≤6	≤6	--
770904	≤6	≤6	≤6	4.22 E5	≤6	≤6	≤6	--
770905	≤6	≤6	≤6	4.96 E5	≤6	≤6	≤6	--
770906	≤6	≤6	≤6	5.16 E5	≤6	≤6	≤6	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number							
	4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
770907	≤6	≤6	≤6	5.16 E5	≤6	≤6	≤6	--
770908	≤6	≤6	9.48 E2	5.13 E5	≤6	≤6	≤6	--
770909	≤6	≤6	--	5.39 E5	≤6	≤6	≤6	--
770910	--	--	3.94 E2	5.60 E5	--	--	--	--
770911	≤6	≤6	3.19 E2	5.13 E5	≤6	≤6	≤6	--
770913	≤6	≤6	3.06 E2	5.42 E5	≤6	≤6	≤6	--
770914	--	--	6.39 E2	5.99 E5	--	--	--	--
770915	≤6	≤6	2.51 E3	5.68 E5	≤6	≤6	≤6	--
770916	--	--	8.90 E2	5.90 E5	--	89	--	--
770917	≤6	≤6	2.82 E3	4.86 E5	≤20	6.38 E3	≤6	--
770918	≤6	≤6	2.33 E3	3.88 E5	8.87 E2	3.30 E4	≤6	--
770919	≤6	≤6	3.29 E3	3.66 E5	1.18 E3	3.59 E4	≤6	--
770920	≤6	≤6	3.31 E3	2.85 E5	4.08 E3	1.55 E5	2.87 E2	--
770921	≤6	≤6	3.45 E3	2.51 E5	6.41 E3	1.25 E5	7.41 E2	--
770922	≤6	≤6	4.64 E3	2.16 E5	4.34 E3	9.87 E4	1.10 E3	--
770923	≤5	≤20	3.44 E3	2.15 E5	4.18 E3	9.66 E4	8.22 E2	--
770924	≤5	≤5	3.95 E3	1.57 E5	3.38 E3	1.06 E5	1.33 E3	--
770925	≤5	≤5	3.85 E3	1.53 E5	2.68 E3	1.02 E5	1.99 E3	--
770926	≤5	≤6	3.10 E3	1.93 E5	3.70 E3	9.71 E4	9.76 E2	--
770927	≤5	≤5	3.08 E3	2.07 E5	3.65 E3	3.24 E5	9.89 E2	--
770928	≤5	31	3.00 E3	6.55 E5	5.71 E3	2.64 E5	1.91 E3	--
770929	≤6	31	3.10 E3	5.81 E5	5.24 E3	2.36 E5	1.59 E3	--
770930	≤7	31	3.50 E3	1.21 E5	7.30 E3	2.12 E5	1.27 E3	--
771001	≤5	28	1.78 E3	7.29 E4	2.94 E3	2.06 E5	1.40 E3	--
771002	≤7	22	3.72 E3	6.66 E4	2.99 E3	1.76 E5	1.01 E3	--
771003	≤10	35	3.77 E3	1.71 E5	5.74 E3	1.82 E5	2.89 E3	--
771004	≤8	37	4.73 E3	1.88 E5	5.94 E3	1.87 E5	1.48 E3	--
771005	≤9	37	5.10 E3	2.02 E5	5.30 E3	1.71 E5	1.23 E3	--
771006	≤8	36	5.04 E3	7.87 E4	5.43 E3	1.73 E5	1.32 E3	5.73 E8
771007	≤5	35	5.18 E3	2.33 E5	5.71 E3	1.79 E5	1.29 E3	--
771008	≤6	34	4.97 E3	2.05 E5	4.48 E3	1.69 E5	9.75 E2	--
771009	≤11	42	5.33 E3	6.49 E4	6.09 E3	2.65 E5	1.63 E3	--
771010	≤8	67	3.80 E3	8.49 E4	2.91 E3	2.11 E5	2.02 E3	--
771011	≤9	74	3.74 E3	1.30 E5	3.15 E3	1.94 E5	1.91 E3	--
771012	≤5	77	4.58 E3	1.36 E5	8.00 E3	1.84 E5	1.52 E3	--
771013	≤9	84	6.02 E3	8.53 E4	7.99 E3	1.77 E5	1.63 E3	--
771014	≤7	78	7.46 E3	1.36 E5	8.54 E3	1.76 E5	1.55 E3	--
771015	≤6	77	1.12 E4	2.55 E5	4.27 E3	2.03 E5	1.69 E3	--
771016	≤7	99	1.03 E4	2.01 E5	4.16 E3	1.85 E5	1.19 E3	--
771017	≤8	82	1.05 E4	2.75 E5	6.22 E3	1.90 E5	1.60 E3	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number 4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
771018	≤6	95	1.30 E4	1.09 E5	4.95 E3	2.00 E5	1.41 E3	--
771019	≤4	82	1.20 E4	2.76 E5	8.70 E3	1.81 E5	1.43 E3	--
771020	≤6	101	1.24 E4	5.14 E5	6.26 E3	1.58 E5	1.46 E3	--
771021	≤5	96	1.32 E4	5.15 E5	6.20 E3	1.82 E5	1.24 E3	--
771022	≤6	87	1.36 E4	5.91 E5	6.92 E3	1.69 E5	1.35 E3	--
771023	≤10	88	1.41 E4	5.56 E5	7.13 E3	1.69 E5	1.40 E3	--
771024	≤7	94	1.65 E4	6.22 E5	6.53 E3	1.79 E5	1.38 E3	--
771025	≤7	91	1.46 E4	6.89 E5	6.06 E3	1.64 E5	1.40 E3	--
771026	≤6	1.12 E2	1.22 E4	2.04 E5	1.07 E4	1.67 E5	6.49 E3	--
771027	2.78 E2	3.99 E2	1.15 E4	1.71 E5	1.53 E4	1.38 E5	6.24 E3	--
771028	≤9	4.55 E2	1.04 E4	4.71 E5	4.65 E3	1.33 E5	3.91 E3	--
771029	≤27	4.92 E2	1.30 E4	4.53 E5	1.76 E4	1.28 E5	4.93 E3	--
771030	≤25	1.84 E2	3.47 E4	4.40 E5	1.41 E4	1.24 E5	3.21 E3	--
771031	≤27	6.31 E2	1.89 E4	5.98 E5	1.19 E4	1.25 E5	3.75 E3	--
771101	≤21	5.80 E2	2.55 E4	1.14 E6	5.24 E3	1.25 E5	4.21 E3	--
771102	≤26	5.47 E2	2.83 E4	1.02 E6	1.03 E4	1.12 E5	3.72 E3	--
771103	≤23	6.04 E2	3.56 E4	6.85 E5	1.36 E4	1.20 E5	3.29 E3	--
771104	≤23	5.74 E2	3.92 E4	1.24 E6	1.18 E4	1.11 E5	1.59 E3	--
771105	≤14	5.43 E2	2.22 E4	7.27 E5	4.36 E3	6.28 E4	1.08 E3	--
771106	≤10	3.44 E2	1.65 E4	3.17 E5	4.39 E3	9.42 E4	1.55 E3	--
771107	≤16	9.73 E2	2.04 E4	6.33 E5	2.76 E4	1.07 E5	3.24 E3	--
771108	≤18	7.04 E2	2.45 E4	1.22 E6	8.40 E3	9.88 E4	4.90 E3	--
771109	≤15	1.34 E3	1.80 E4	4.75 E5	7.89 E3	9.94 E4	3.62 E3	5.71 E7
771110	≤18	6.15 E2	1.97 E4	7.56 E5	7.06 E3	9.70 E4	6.41 E3	--
771111	≤22	7.78 E2	1.64 E4	6.37 E5	6.73 E3	9.96 E4	2.82 E3	--
771112	≤34	1.51 E3	3.03 E4	1.48 E6	1.26 E4	9.25 E4	2.17 E3	--
771113	≤28	1.37 E3	6.04 E4	5.61 E5	1.05 E4	9.69 E4	3.60 E3	--
771114	≤28	1.58 E3	5.17 E4	1.40 E6	1.57 E4	1.01 E5	5.94 E3	--
771115	≤27	1.30 E3	4.76 E4	1.47 E6	1.35 E4	7.52 E4	4.14 E3	--
771116	≤23	1.59 E3	4.75 E4	2.20 E6	6.12 E3	7.27 E4	4.62 E3	--
771117	≤27	1.30 E3	6.78 E4	2.05 E6	6.64 E3	1.06 E5	5.57 E3	--
771118	≤32	2.43 E3	8.75 E4	2.28 E6	5.57 E3	7.45 E4	2.08 E3	--
771120	62	1.91 E3	9.78 E4	8.41 E5	2.16 E4	7.60 E4	3.30 E3	2.29 E7
771121	≤35	2.48 E3	9.48 E4	7.72 E5	1.03 E4	7.93 E4	4.58 E3	--
771123	≤14	2.39 E3	1.45 E5	7.78 E5	3.74 E4	1.91 E5	1.83 E3	--
771125	≤13	9.81 E2	1.13 E5	7.32 E5	1.79 E4	2.07 E5	2.72 E3	--
771128	≤16	1.19 E3	1.45 E5	7.15 E5	1.22 E4	1.74 E5	2.37 E3	--
771130	≤14	1.37 E3	6.74 E4	6.50 E5	1.51 E4	1.97 E5	1.80 E3	--
771202	≤18	8.45 E2	1.03 E5	5.68 E5	1.17 E4	2.22 E5	1.79 E3	--
771205	≤29	1.70 E3	7.76 E4	4.98 E5	1.12 E4	2.14 E5	1.23 E3	3.26 E7
771207	32	7.57 E2	1.36 E5	4.64 E5	9.18 E3	2.03 E5	9.83 E2	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number 4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
771209	≤29	1.10 E3	1.07 E5	4.70 E5	1.16 E4	1.79 E5	1.08 E3	--
771212	40	1.78 E3	1.60 E5	5.45 E5	1.13 E4	1.61 E5	1.09 E3	--
771214	≤32	1.60 E3	1.65 E5	4.72 E5	1.61 E4	1.37 E5	5.87 E2	--
771216	≤30	1.59 E3	1.44 E5	6.75 E5	1.33 E4	1.28 E5	1.06 E3	--
771218	--	--	--	--	--	--	--	2.75E7
771219	≤34	1.69 E3	1.73 E5	1.27 E6	9.84 E3	1.15 E5	1.19 E3	1.95E7
771221	≤30	1.98 E3	1.73 E5	1.99 E6	1.70 E4	1.04 E5	1.10 E3	--
771223	96	3.26 E3	2.47 E5	2.04 E6	4.51 E3	1.22 E5	5.55 E2	--
771226	≤22	4.11 E3	2.75 E5	7.56 E5	3.41 E4	3.58 E5	1.79 E3	1.97E7
771228	≤28	3.29 E3	3.21 E5	3.13 E6	4.24 E4	3.79 E5	2.21 E3	--
771230	≤28	5.59 E3	3.22 E5	3.55 E6	4.57 E4	3.63 E5	2.14 E3	--
780102	≤27	6.24 E3	3.25 E5	4.56 E6	9.81 E3	3.00 E5	2.57 E3	1.66E7
780104	≤22	5.61 E3	3.19 E5	2.65 E6	3.20 E4	2.79 E5	2.02 E3	--
780106	≤17	2.67 E3	3.17 E5	4.58 E6	2.69 E4	2.59 E5	1.64 E3	--
780109	32	2.68 E3	3.29 E5	2.79 E6	3.16 E4	3.66 E5	2.16 E3	1.51E7
780111	≤36	7.33 E3	5.83 E5	3.62 E6	6.66 E4	3.67 E5	1.88 E3	--
780113	32	6.71 E3	4.79 E5	4.65 E6	6.37 E4	3.61 E5	1.93 E3	--
780116	≤26	6.28 E3	4.57 E5	3.15 E6	5.71 E4	3.19 E5	1.76 E3	1.42E7
780118	≤19	1.06 E4	6.24 E5	3.49 E6	6.16 E4	4.90 E5	1.16 E3	--
780120	≤21	6.16 E3	8.42 E5	4.05 E6	7.15 E4	4.03 E5	1.47 E3	--
780123	≤17	6.75 E3	8.12 E5	5.78 E6	8.24 E4	3.50 E5	1.30 E3	1.30E7
780125	≤16	8.53 E3	9.14 E5	6.05 E6	8.29 E4	3.12 E5	1.22 E3	--
780127	≤6	1.40 E4	1.10 E6	6.94 E6	1.00 E5	2.90 E5	1.40 E3	--
780130	≤27	1.60 E4	9.56 E5	6.69 E6	1.10 E5	2.74 E5	1.11 E3	1.16E7
780201	≤26	1.54 E4	9.28 E5	6.44 E6	1.11 E5	2.69 E5	1.07 E3	--
780203	38	1.56 E4	8.75 E5	6.21 E6	1.07 E5	2.54 E5	9.28 E2	--
780206	42	1.50 E4	8.15 E5	6.90 E6	1.01 E5	2.35 E5	8.19 E2	9.75E6
780208	45	1.49 E4	7.90 E5	7.21 E6	9.88 E4	2.23 E5	7.56 E2	--
780210	45	1.51 E4	8.21 E5	7.43 E6	9.67 E4	2.17 E5	9.64 E2	--
780213	37	1.43 E4	7.68 E5	7.54 E6	8.66 E4	1.91 E5	6.89 E2	1.46E7
780215	≤34	1.45 E4	7.39 E5	7.69 E6	8.77 E4	1.85 E5	7.56 E2	--
780217	33	1.59 E4	7.79 E5	7.43 E6	9.09 E4	1.82 E5	7.33 E2	--
780220	≤39	1.76 E4	7.51 E5	7.92 E6	9.49 E4	1.74 E5	7.07 E2	--
780222	≤36	1.82 E4	7.07 E5	8.25 E6	9.09 E4	1.68 E5	6.88 E2	6.49E6
780224	≤33	1.89 E4	7.64 E5	8.39 E6	1.06 E5	1.64 E5	6.91 E2	--
780227	≤33	2.05 E4	7.32 E5	8.82 E6	1.20 E5	1.59 E5	6.73 E2	5.93E6
780301	≤27	2.22 E4	7.66 E5	8.75 E6	1.31 E5	1.55 E5	6.80 E2	--
780303	≤39	2.44 E4	7.81 E5	8.50 E6	1.50 E5	2.36 E5	6.74 E2	--
780306	40	3.45 E4	7.76 E5	8.20 E6	2.61 E5	3.10 E5	6.32 E2	7.73E6
780308	43	3.61 E4	7.37 E5	8.03 E6	2.60 E5	2.55 E5	5.53 E2	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number							
	4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
780310	53	3.66 E4	7.37 E5	7.53 E6	2.46 E5	2.84 E5	5.74 E2	6.23 E6
780311	--	--	--	--	--	--	--	3.81 E6
780313	43	3.88 E4	7.03 E5	6.89 E6	2.68 E5	2.53 E5	5.80 E2	--
780314	--	--	--	--	--	--	--	3.19 E6
780315	44	3.69 E4	7.09 E5	6.47 E6	2.59 E5	2.22 E5	6.06 E2	--
780317	38	3.70 E4	6.96 E5	6.06 E6	2.53 E5	2.14 E5	5.53 E2	2.33 E6
780320	≤38	3.34 E4	6.24 E5	5.62 E6	2.34 E5	1.91 E5	4.46 E2	2.22 E6
780322	37	3.33 E4	5.88 E5	5.39 E6	2.26 E5	1.81 E5	4.00 E2	--
780324	≤39	3.24 E4	5.64 E5	5.15 E6	2.18 E5	1.71 E5	3.63 E2	--
780327	≤33	3.27 E4	5.49 E5	5.09 E6	2.09 E5	1.60 E5	3.30 E2	2.01 E6
780328	--	--	--	--	--	--	--	6.19 E5
780329	≤27	3.53 E4	5.41 E5	5.09 E6	2.02 E5	1.50 E5	3.11 E2	--
780331	≤25	3.76 E4	5.39 E5	5.15 E6	1.98 E5	1.44 E5	2.66 E2	3.94 E6
780403	≤28	4.00 E4	5.66 E5	5.55 E6	1.90 E5	1.36 E5	2.68 E2	5.98 E5
780405	≤32	4.25 E4	5.89 E5	5.69 E6	1.87 E5	1.31 E5	2.49 E2	--
780407	≤32	4.46 E4	6.14 E5	5.96 E6	1.83 E5	1.28 E5	2.63 E2	2.80 E5
780410	45	4.28 E4	6.03 E5	5.84 E6	1.69 E5	1.12 E5	2.54 E2	6.42 E5
780412	42	4.42 E4	6.20 E5	6.02 E6	1.69 E5	1.11 E5	2.51 E2	--
780414	43	4.44 E4	6.37 E5	6.28 E6	1.73 E5	1.09 E5	2.63 E2	--
780417	36	4.54 E4	6.62 E5	6.92 E6	1.89 E5	1.07 E5	2.94 E2	8.37 E5
780419	38	4.87 E4	6.65 E5	6.00 E6	2.17 E5	2.33 E5	3.19 E2	--
780421	40	5.40 E4	6.47 E5	5.75 E6	2.27 E5	2.16 E5	3.00 E2	--
780424	≤25	6.49 E4	7.23 E5	6.63 E6	2.39 E5	2.11 E5	2.49 E2	1.67 E6
780426	≤23	6.70 E4	7.54 E5	6.50 E6	2.33 E5	2.95 E5	2.82 E2	
780428	≤23	7.94 E4	7.57 E5	6.21 E6	2.44 E5	3.75 E5	4.54 E2	--
780501	≤19	7.53 E4	5.73 E5	7.18 E6	2.29 E5	3.33 E5	4.72 E2	1.78 E6
780503	≤22	7.43 E4	7.00 E5	5.59 E6	2.20 E5	3.15 E5	3.47 E2	--
780505	≤22	7.43 E4	6.96 E5	4.17 E6	2.23 E5	4.10 E5	9.31 E2	--
780508	≤24	7.28 E4	6.62 E5	4.62 E6	2.33 E5	3.61 E5	8.61 E2	--
780510	≤21	6.20 E4	6.59 E5	4.17 E6	2.34 E5	3.72 E5	8.95 E2	2.15 E6
780512	≤17	6.20 E4	6.53 E5	3.77 E6	2.24 E5	3.58 E5	8.52 E2	--
780515	≤38	5.57 E4	6.65 E5	3.52 E6	2.00 E5	2.96 E5	6.63 E2	1.83 E6
780517	≤33	5.43 E4	5.57 E5	3.39 E6	1.88 E5	2.74 E5	5.72 E2	--
780519	≤33	5.30 E4	5.23 E5	3.29 E6	1.88 E5	2.63 E5	5.20 E2	--
780522	≤34	5.20 E4	4.95 E5	3.11 E6	1.81 E5	2.42 E5	4.59 E2	1.54 E6
780526	≤38	5.16 E4	5.13 E5	3.38 E6	1.75 E5	2.30 E5	4.33 E2	--
780530	≤45	5.40 E4	5.68 E5	4.39 E6	1.75 E5	2.30 E5	4.80 E2	1.40 E6
780602	≤45	5.38 E4	5.83 E5	4.89 E6	1.79 E5	2.23 E5	4.93 E2	--
780605	35	5.39 E4	6.46 E5	4.84 E6	1.99 E5	2.22 E5	5.33 E2	1.39 E6
780609	43	5.41 E4	5.48 E5	4.09 E6	2.73 E5	2.83 E5	8.08 E2	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number 4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
780612	46	5.75 E4	4.85 E5	3.79 E6	2.54 E5	2.29 E5	6.56 E2	1.21 E6
780616	≤41	5.85 E4	5.63 E5	4.01 E6	2.51 E5	2.20 E5	6.42 E2	--
780619	≤50	5.85 E4	5.91 E5	4.28 E6	2.59 E5	2.23 E5	6.41 E2	1.19 E6
780623	≤45	5.89 E4	6.34 E5	4.73 E6	2.60 E5	2.15 E5	6.37 E2	--
780626	≤19	6.16 E4	6.71 E5	5.31 E6	2.86 E5	2.16 E5	6.93 E2	1.16 E6
780630	≤52	6.11 E4	7.30 E5	5.76 E6	3.33 E5	2.07 E5	7.14 E2	--
780703	66	6.47 E4	8.05 E5	6.09 E6	4.07 E5	2.10 E5	7.63 E2	1.30 E5
780707	76	6.45 E4	8.20 E5	6.76 E6	4.83 E5	1.96 E5	7.50 E2	--
780710	87	5.76 E4	7.50 E5	6.27 E6	4.84 E5	1.69 E5	7.02 E2	1.46 E6
780714	81	5.11 E4	7.52 E5	6.53 E6	5.73 E5	1.60 E5	7.15 E2	--
780717	97	5.24 E4	7.30 E5	5.92 E6	6.26 E5	1.80 E5	3.22 E2	1.69 E6
780721	98	5.33 E4	7.55 E5	6.25 E6	6.82 E5	1.73 E5	4.13 E2	--
780724	1.36 E2	5.09 E4	7.78 E5	6.72 E6	7.29 E5	1.69 E5	4.58 E2	2.43 E6
780728	1.14 E2	4.95 E4	7.67 E5	6.59 E6	7.90 E5	1.56 E5	4.77 E2	--
780731	1.12 E2	5.16 E4	7.82 E5	6.99 E6	8.60 E5	1.56 E5	4.95 E2	5.05 E6
780804	1.27 E2	5.09 E4	7.76 E5	7.17 E6	9.43 E5	1.47 E5	5.46 E2	--
780807	1.02 E2	4.14 E4	6.81 E5	5.94 E6	8.33 E5	1.47 E5	5.00 E2	6.13 E6
780811	79	3.43 E4	6.07 E5	4.31 E6	5.95 E5	2.68 E5	3.88 E2	--
780814	≤53	2.06 E4	4.20 E5	3.11 E6	3.04 E5	2.88 E5	1.02 E3	1.02 E5
780818	≤65	3.36 E4	4.42 E5	3.05 E6	3.17 E5	2.29 E5	1.02 E2	--
780821	51	2.96 E4	4.62 E5	3.57 E6	4.14 E5	1.61 E5	1.31 E3	2.22 E5
780825	48	4.31 E4	5.27 E5	4.60 E6	4.20 E5	2.47 E5	1.18 E3	--
780828	50	4.01 E4	5.28 E5	5.42 E6	2.22 E5	2.26 E5	1.09 E3	3.53 E5
780901	52	4.22 E4	6.14 E5	5.69 E6	3.94 E5	2.05 E5	1.29 E3	--
780905	62	3.13 E4	6.75 E5	5.27 E6	5.49 E5	2.03 E5	1.23 E3	4.57 E5
780908	54	3.53 E4	6.51 E5	5.38 E6	3.60 E5	1.83 E5	1.28 E3	--
780911	57	2.89 E4	6.64 E5	5.71 E6	5.93 E5	2.01 E5	1.44 E3	6.37 E5
780915	63	3.76 E4	7.08 E5	6.28 E6	3.99 E5	1.73 E5	1.29 E3	--
780918	60	3.48 E4	7.13 E5	6.73 E6	7.30 E5	1.76 E5	1.28 E3	7.92 E5
780925	88	3.84 E4	7.51 E5	8.73 E6	8.73 E5	1.70 E5	1.44 E3	1.81 E6
781003	94	3.62 E4	7.68 E5	7.81 E6	1.18 E6	1.66 E5	1.45 E3	3.88 E6
781016	65	3.21 E4	6.51 E5	7.53 E6	1.19 E6	1.12 E5	1.12 E3	--
781030	1.02 E2	2.87 E4	6.71 E5	7.48 E6	1.77 E6	9.76 E4	1.10 E3	--
781113	1.49 E2	3.37 E4	6.31 E5	7.43 E6	2.38 E6	8.48 E4	9.52 E2	--
781127	1.17 E2	3.69 E4	6.09 E5	6.23 E6	2.03 E6	1.94 E5	7.64 E2	1.03 E6
781204	42	1.33 E4	4.39 E5	4.59 E6	4.10 E5	3.07 E5	1.27 E3	5.03 E6
781208	50	9.33 E4	4.50 E5	3.60 E6	1.33 E6	2.78 E5	1.15 E3	5.99 E6
781211	46	1.10 E5	3.78 E5	4.05 E6	1.25 E6	2.47 E5	1.21 E3	2.97 E6
781218	35	1.17 E5	4.21 E5	4.06 E6	2.34 E5	1.86 E5	9.85 E2	2.12 E6
781227	37	1.13 E5	4.32 E5	3.95 E6	6.34 E5	1.72 E5	8.18 E2	1.13 E6

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number 4-4	4-5	4-6	4-7	4-8	4-9	4-10	4-11
790104	38	1.02 E5	5.07 E5	3.19 E6	3.23 E5	1.95 E5	6.18 E2	1.06 E6
790111	79	1.46 E5	3.49 E5	3.05 E6	2.90 E5	2.15 E5	5.01 E2	9.14 E5
790115	≤33	6.40 E4	2.97 E5	3.18 E6	2.94 E5	1.84 E5	4.28 E2	8.64 E5
790122	46	4.74 E4	3.75 E5	2.87 E6	3.20 E5	2.82 E5	3.78 E2	8.46 E5
790129	≤39	6.98 E4	3.37 E5	2.94 E6	3.67 E5	2.25 E5	2.73 E2	6.13 E5
790206	≤35	8.64 E4	2.86 E5	2.76 E6	3.30 E5	1.74 E5	2.53 E2	4.63 E5
790212	≤45	9.52 E4	3.19 E5	2.97 E6	3.42 E5	1.48 E5	2.00 E2	3.28 E5
790305	≤53	1.35 E5	4.77 E5	2.25 E6	5.92 E5	2.05 E5	4.32 E2	1.96 E5
790313	≤65	1.17 E5	4.07 E5	1.96 E6	5.32 E5	1.58 E5	3.09 E2	1.66 E5
790326	≤66	1.15 E5	3.45 E5	1.69 E6	4.36 E5	1.40 E5	2.58 E2	1.36 E5
790409	≤62	1.12 E5	3.30 E5	1.44 E6	3.80 E5	1.32 E5	3.35 E2	1.58 E5
790423	59	8.62 E4	2.82 E5	1.07 E6	3.15 E5	1.34 E5	3.55 E2	1.32 E5
790507	46	8.96 E4	3.56 E5	1.17 E6	2.61 E5	1.44 E5	2.56 E2	1.16 E5
790521	50	9.19 E4	6.37 E5	1.59 E6	3.06 E5	1.23 E5	2.42 E2	9.87 E4
790604	45	3.88 E4	3.22 E5	9.32 E5	3.03 E5	1.39 E5	7.20 E2	7.62 E4
790619	≤96	6.40 E4	3.84 E5	9.86 E5	2.86 E5	1.21 E5	5.64 E2	1.01 E5
790702	1.09 E2	7.20 E4	8.20 E5	1.85 E6	6.34 E5	1.35 E5	5.39 E2	1.02 E5
790716	≤22	6.28 E4	6.72 E5	1.57 E6	6.49 E5	1.51 E5	4.50 E2	2.46 E5
800527	2.01 E2	7.80 E4	4.18 E5	4.31 E5	2.65 E5	8.61 E4	1.45 E2	7.68 E3
810526	7.08 E2	4.94 E4	1.43 E5	2.78 E5	2.78 E5	2.40 E4	2.46 E2	9.90 E3
820524	5.52 E2	1.16 E4	5.93 E4	8.52 E4	8.16 E4	1.49 E4	2.16 E2	7.38 E3

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Site in burial ground 6

Date yymmdd	Well number							
	6-4	6-5	6-6	6-7	6-8	6-9	6-10	6-11
770703	≤6	≤6	≤6	≤6	≤6	≤6	≤6	≤6
770713	3.38 E2	3.79 E2	9.91 E2	4.25 E2	4.59 E2	4.16 E2	2.76 E2	1.12 E3
770714	--	--	--	--	--	--	--	1.46 E10
770715	3.69 E3	1.88 E4	1.07 E4	1.24 E4	8.20 E3	3.23 E4	2.56 E4	--
770716	2.69 E3	1.64 E3	9.19 E3	1.43 E3	4.76 E3	1.67 E3	1.14 E3	--
770717	9.90 E1	2.49 E3	1.15 E2	1.13 E2	1.35 E2	1.32 E2	1.30 E2	--
770718	2.54 E3	1.21 E3	5.14 E3	2.65 E2	2.56 E2	7.47 E2	3.58 E2	--
770719	1.93 E3	2.02 E2	8.80 E1	1.98 E2	1.82 E2	1.55 E2	1.17 E2	--
770720	≤6	2.00 E2	≤6	≤6	≤6	≤6	≤6	--
770721	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770722	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770723	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770724	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770725	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770726	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770727	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770728	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770731	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770801	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770802	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770803	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770804	≤6	≤6	--	--	--	--	--	--
770805	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770806	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770807	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770809	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770810	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770812	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770814	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770817	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770820	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770821	--	--	--	--	--	--	--	1.26 E7
770823	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770824	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770825	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770826	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770827	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770828	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770829	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770831	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number 6-4	6-5	6-6	6-7	6-8	6-9	6-10	6-11
770901	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770902	--	--	--	--	--	--	--	9.28 E6
770903	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770905	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770907	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770910	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770912	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770914	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770916	≤6	≤6	≤6	≤6	≤6	≤6	≤6	--
770920	≤8	≤8	≤8	≤8	≤8	≤8	≤8	--
770922	≤8	≤9	≤5	≤5	≤9	≤6	≤6	--
770924	≤10	≤13	≤5	≤2	≤13	≤5	≤5	--
770926	≤12	≤5	≤5	≤5	≤5	≤5	≤5	--
770928	≤5	≤5	≤5	≤5	≤5	≤5	≤5	--
770930	≤5	≤5	≤5	≤5	≤5	≤5	≤5	--
771002	≤5	≤5	≤5	≤5	≤5	≤5	≤5	--
771004	≤5	≤5	≤5	≤5	≤5	≤5	≤5	--
771006	≤5	≤5	≤5	≤5	≤5	≤5	≤5	7.57 E7
771008	≤11	≤11	≤5	≤11	≤8	≤8	≤12	--
771010	≤10	≤8	≤8	≤8	≤8	≤9	≤6	--
771012	≤6	≤12	≤8	≤8	≤8	≤8	≤5	--
771014	≤4	≤5	≤4	≤6	≤6	≤5	≤4	--
771016	≤8	≤5	≤5	≤8	≤4	≤6	≤10	--
771018	≤4	≤5	≤4	≤6	≤8	≤6	≤5	--
771020	≤8	≤6	≤6	≤4	≤6	≤4	≤6	--
771022	≤6	≤6	≤7	≤9	≤10	≤7	≤13	--
771024	≤10	≤7	≤6	≤7	≤14	≤7	≤9	--
771026	≤7	≤6	≤6	≤7	≤15	≤7	≤6	--
771028	≤7	≤9	≤8	≤7	≤16	≤7	≤9	--
771030	≤20	≤24	≤21	≤23	≤26	≤22	≤25	--
771101	≤20	≤18	≤17	≤18	≤33	≤19	≤22	--
771103	≤25	≤22	≤23	≤27	35	≤22	≤14	--
771105	≤17	≤15	≤12	≤12	43	≤12	≤17	--
771107	≤17	≤12	≤10	≤12	57	≤17	≤15	--
771109	≤14	≤15	≤13	≤16	68	≤11	≤17	3.03 E5
771111	≤17	≤13	≤14	≤10	93	≤12	≤18	--
771113	≤17	≤15	≤9	≤9	1.05 E2	≤12	≤17	--
771115	≤14	≤8	≤10	≤11	1.40 E2	≤26	≤19	--
771117	≤13	≤12	≤8	≤9	2.18 E2	≤7	≤13	--
771120	≤13	≤10	≤10	≤17	3.06 E2	≤23	≤16	5.95 E4

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number							
	6-4	6-5	6-6	6-7	6-8	6-9	6-10	6-11
771121	≤18	≤14	≤11	≤12	3.47 E2	≤12	≤14	--
771123	≤11	≤13	≤13	≤13	4.00 E2	≤10	≤14	--
771125	≤14	≤12	≤7	≤10	3.05 E2	≤14	≤14	--
771128	≤8	≤6	≤8	≤15	4.99 E2	≤12	≤10	--
771130	≤13	≤9	≤10	≤6	5.53 E2	≤12	≤14	--
771202	≤11	≤10	≤13	≤18	6.86 E2	≤10	≤14	--
771205	≤21	≤19	≤22	≤24	1.77 E3	≤22	≤20	4.54 E4
771207	≤22	≤22	≤19	≤30	2.07 E3	≤19	≤20	--
771209	≤21	≤18	≤25	46	2.78 E3	≤20	≤27	--
771212	≤33	≤24	70	1.65 E2	4.53 E3	≤29	32	7.22 E4
771214	≤31	≤19	≤17	3.04 E2	5.62 E3	≤20	≤23	--
771216	34	≤22	≤17	4.99 E2	6.28 E3	≤20	≤21	--
771219	60	≤26	≤28	1.11 E3	8.55 E3	≤28	≤25	4.11 E4
771221	61	≤21	≤13	1.39 E3	1.12 E4	≤11	≤16	--
771223	52	≤14	≤10	2.16 E3	1.06 E4	≤13	≤17	--
771226	98	≤10	≤12	2.37 E3	1.68 E4	≤15	≤21	1.27 E4
771228	1.31 E2	≤24	≤23	3.66 E3	1.38 E4	≤16	≤23	--
771230	1.19 E2	≤33	≤10	6.02 E3	2.06 E4	≤13	≤15	--
780102	1.31 E2	69	≤11	9.47 E3	2.82 E4	≤17	≤15	1.81 E4
780104	1.87 E2	1.32 E2	≤10	1.33 E4	3.36 E4	≤17	≤16	--
780106	1.91 E2	1.97 E2	≤60	1.48 E4	3.73 E4	≤10	≤18	--
780109	2.46 E2	2.48 E2	≤12	1.87 E4	3.40 E4	≤16	≤28	2.75 E4
780111	2.12 E2	2.59 E2	≤23	1.97 E4	3.05 E4	≤25	≤34	--
780113	1.62 E2	2.97 E2	≤22	2.87 E4	4.68 E4	≤31	≤37	--
780116	1.60 E2	5.10 E2	≤9	4.09 E4	4.83 E4	≤6	≤19	2.81 E4
780118	2.01 E2	7.47 E2	≤6	4.90 E4	3.99 E4	≤7	≤12	--
780120	2.91 E2	8.37 E2	≤21	5.24 E4	5.07 E4	≤6	≤17	--
780123	2.30 E2	7.26 E2	≤6	5.70 E4	5.55 E4	≤6	≤12	2.12 E4
780125	2.70 E2	9.50 E2	≤6	6.98 E4	5.68 E4	≤6	≤17	--
780127	3.40 E2	7.50 E2	≤6	1.94 E4	4.50 E4	≤6	≤6	--
780130	2.98 E2	1.26 E3	≤6	5.74 E4	4.69 E4	≤7	≤25	3.08 E4
780201	3.14 E2	2.05 E3	≤21	8.01 E4	5.12 E4	≤27	≤43	--
780203	3.53 E2	4.72 E3	≤20	1.03 E5	5.84 E4	≤27	35	--
780206	4.55 E2	7.23 E3	≤23	1.76 E5	5.69 E4	≤37	46	2.87 E4
780208	3.35 E2	7.68 E3	≤29	2.34 E5	8.42 E4	≤38	46	--
780210	3.45 E2	8.62 E3	≤27	2.43 E5	1.03 E5	≤33	48	--
780213	3.24 E2	8.99 E3	≤13	2.88 E5	1.08 E5	≤21	39	2.64 E4
780215	3.84 E2	7.94 E3	≤18	3.35 E5	1.14 E5	≤21	≤32	--
780217	4.03 E2	8.60 E3	38	3.42 E5	1.47 E5	≤22	39	--
780220	5.03 E2	8.89 E3	56	3.87 E5	2.11 E5	≤14	36	--

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number							
	6-4	6-5	6-6	6-7	6-6	6-9	6-10	6-11
780222	6.56 E2	9.73 E3	1.40 E2	4.19 E5	2.12 E5	≤15	35	1.72 E4
780224	6.79 E2	1.08 E4	1.72 E2	4.36 E5	2.31 E5	≤20	≤39	--
780227	6.61 E2	1.28 E4	3.71 E2	4.82 E5	2.60 E5	≤24	40	1.72 E4
780301	7.05 E2	1.34 E4	4.10 E2	4.98 E5	2.81 E5	≤32	≤40	--
780303	6.70 E2	1.46 E4	4.62 E2	5.37 E5	2.99 E5	≤36	≤39	--
780306	7.14 E2	1.60 E4	1.38 E2	5.49 E5	2.75 E5	≤33	47	5.07 E3
780308	8.11 E2	1.64 E4	3.68 E2	5.71 E5	2.80 E5	35	54	--
780310	6.77 E2	1.77 E4	2.53 E2	5.50 E5	2.67 E5	≤32	44	--
780313	7.79 E2	1.90 E4	≤23	4.59 E5	1.22 E5	≤27	53	8.50 E2
780315	8.34 E2	1.89 E4	≤16	4.71 E5	1.21 E5	≤27	51	--
780317	9.04 E2	1.87 E4	≤22	5.02 E5	1.11 E5	≤26	50	--
780320	1.13 E3	2.06 E4	≤18	5.31 E5	1.20 E5	≤21	39	3.68 E2
780322	1.37 E3	2.49 E4	≤14	5.08 E5	1.27 E5	≤24	56	--
780327	1.42 E3	3.36 E4	≤8	5.63 E5	1.56 E5	≤27	37	3.24 E2
780329	1.38 E3	3.83 E4	≤18	5.88 E5	1.75 E5	≤26	42	--
780331	1.83 E3	4.03 E4	≤38	6.16 E5	1.97 E5	≤32	46	--
780403	1.63 E3	4.66 E4	6.45 E2	6.17 E5	2.49 E5	≤32	43	3.70 E2
780405	1.85 E3	5.17 E4	1.45 E3	6.47 E5	2.72 E5	33	41	--
780407	1.90 E3	5.26 E4	1.92 E3	6.60 E5	3.05 E5	48	50	--
780410	1.59 E3	5.32 E4	2.21 E3	6.57 E5	2.95 E5	49	52	4.71 E2
780412	1.79 E3	5.12 E4	2.47 E3	6.57 E5	3.01 E5	53	53	--
780414	1.21 E3	5.44 E4	2.66 E3	7.16 E5	3.05 E5	61	41	--
780417	1.17 E3	5.53 E4	3.24 E3	7.92 E5	3.27 E5	68	45	7.89 E2
780419	1.07 E3	5.56 E4	3.35 E3	8.11 E5	3.30 E5	68	51	--
780421	9.82 E2	5.25 E4	3.22 E3	8.24 E5	3.25 E5	72	54	--
780424	7.71 E2	6.82 E4	4.31 E3	9.35 E5	3.62 E5	66	≤39	1.25 E3
780426	6.15 E2	7.22 E4	4.39 E3	9.41 E5	3.63 E5	68	≤38	--
780428	6.14 E2	6.73 E4	4.10 E3	9.69 E5	3.64 E5	68	≤36	--
780501	5.60 E2	7.65 E4	4.43 E3	9.29 E5	3.73 E5	78	≤40	1.47 E3
780503	4.77 E2	7.95 E4	4.56 E3	9.38 E5	3.66 E5	73	≤43	--
780505	5.14 E2	7.89 E4	4.05 E3	9.57 E5	3.72 E5	≤39	≤38	--
780508	1.05 E3	6.92 E4	3.08 E3	9.29 E5	3.57 E5	≤26	≤39	--
780510	1.14 E3	6.82 E4	1.97 E3	8.30 E5	3.31 E5	≤8	≤20	1.02 E3
780512	1.00 E3	6.47 E4	1.56 E3	8.41 E5	2.74 E5	≤7	≤13	--
780515	8.98 E2	6.03 E4	2.01 E3	7.45 E5	2.37 E5	≤32	≤48	3.91 E2
780517	8.66 E2	6.40 E4	2.14 E3	7.11 E5	2.44 E5	≤32	≤46	--
780519	9.32 E2	7.13 E4	2.38 E3	7.09 E5	2.52 E5	≤38	≤55	--
780522	8.91 E2	8.00 E4	3.06 E3	7.06 E5	2.73 E5	≤45	≤53	5.90 E2
780526	9.20 E2	8.68 E4	3.28 E3	7.65 E5	2.98 E5	≤62	≤60	--
780530	8.68 E2	9.49 E4	3.74 E3	8.22 E5	3.14 E5	64	51	6.08 E2

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number							
	6-4	6-5	6-6	6-7	6-8	6-9	6-10	6-11
780602	7.33 E2	9.63 E4	4.06 E3	8.90 E5	3.18 E5	71	57	--
780605	6.53 E2	9.36 E4	4.15 E3	9.72 E5	3.31 E5	71	56	6.16 E2
780609	6.71 E2	7.51 E4	3.41 E3	8.78 E5	3.41 E5	36	35	--
780612	7.29 E2	7.65 E4	1.70 E3	8.61 E5	2.54 E5	≤25	≤41	2.92 E2
780616	7.42 E2	1.14 E5	2.72 E3	8.00 E5	2.61 E5	≤33	≤46	--
780619	7.35 E2	1.24 E5	3.24 E3	7.90 E5	2.79 E5	≤38	≤48	2.17 E2
780623	7.22 E2	1.26 E5	3.40 E3	8.56 E5	2.94 E5	≤48	44	--
780626	6.89 E2	1.32 E5	4.11 E3	9.67 E5	3.17 E5	51	62	4.91 E2
780630	5.25 E2	1.35 E5	4.39 E3	1.06 E6	3.25 E5	56	54	--
780703	5.05 E2	1.39 E5	5.05 E3	1.20 E6	3.41 E5	62	54	7.39 E2
780707	4.48 E2	1.68 E5	5.49 E3	1.26 E6	3.42 E5	67	64	--
780710	4.02 E2	1.27 E5	5.31 E3	1.18 E6	3.12 E5	53	≤49	1.62 E3
780714	3.98 E2	1.26 E5	5.56 E3	1.21 E6	3.13 E5	57	≤57	--
780717	3.61 E2	1.17 E5	5.09 E3	1.23 E6	3.16 E5	52	≤52	3.17 E3
780721	3.62 E2	1.00 E5	5.41 E3	1.21 E6	3.13 E5	53	≤49	--
780724	3.78 E2	1.05 E5	5.78 E3	1.24 E6	3.20 E5	73	61	5.93 E3
780728	3.79 E2	9.67 E4	5.85 E3	1.25 E6	3.20 E5	77	57	--
780731	3.45 E2	1.01 E5	6.03 E3	1.21 E6	3.27 E5	58	42	9.99 E3
780804	3.54 E2	1.12 E5	5.74 E3	1.10 E6	3.24 E5	59	39	--
780807	3.28 E2	1.02 E5	5.14 E3	1.18 E6	3.03 E5	≤43	42	1.57 E4
780811	3.12 E2	9.82 E4	4.36 E3	9.53 E5	2.98 E5	≤43	44	--
780814	2.46 E2	8.83 E4	2.10 E3	1.24 E6	2.90 E5	≤32	≤76	7.44 E3
780818	5.56 E2	1.29 E5	1.83 E3	6.79 E5	2.75 E5	≤36	≤56	--
780821	5.14 E2	1.46 E5	1.56 E3	7.48 E5	2.76 E5	≤32	50	5.62 E2
780825	4.61 E2	1.60 E5	1.59 E3	9.05 E5	2.84 E5	≤43	54	--
780828	4.21 E2	1.64 E5	1.72 E3	9.58 E5	2.90 E5	≤37	37	7.13 E2
780901	3.61 E2	1.69 E5	1.75 E3	7.04 E5	2.95 E5	≤41	43	--
780905	3.65 E2	1.67 E5	1.82 E3	7.02 E5	2.95 E5	41	55	1.43 E3
780908	3.57 E2	1.68 E5	1.84 E3	8.02 E5	2.79 E5	45	60	--
780911	3.64 E2	1.69 E5	2.00 E3	1.01 E6	2.87 E5	45	57	3.82 E3
780915	3.68 E2	1.56 E5	1.97 E3	1.05 E6	2.86 E5	46	63	--
780918	3.60 E2	1.53 E5	2.12 E3	9.59 E5	3.04 E5	≤40	43	1.59 E4
780922	3.60 E2	1.45 E5	2.15 E3	1.04 E6	3.09 E5	51	48	--
780925	3.68 E2	1.51 E5	2.41 E3	9.97 E5	3.28 E5	50	48	3.84 E4
780929	3.65 E2	1.43 E5	2.36 E3	8.81 E5	3.25 E5	45	42	--
781002	3.86 E2	1.43 E5	2.71 E3	1.20 E6	3.38 E5	65	46	5.37 E4
781006	4.38 E2	1.31 E5	2.75 E3	1.61 E6	3.37 E5	76	81	--
781011	3.68 E2	1.04 E5	3.03 E3	1.30 E6	3.04 E5	50	36	5.40 E4
781013	3.76 E2	9.83 E4	2.90 E3	1.38 E6	2.94 E5	67	35	--
781016	3.32 E2	9.10 E4	3.03 E3	1.46 E6	3.05 E5	55	41	5.05 E4

APPENDIX 1. ANALYSES OF WATER SAMPLES FOR TRITIUM—Continued

Date yymmdd	Well number 6-4	6-5	6-6	6-7	6-8	6-9	6-10	6-11
781020	3.80 E2	8.95 E4	3.28 E3	1.56 E6	3.23 E5	54	33	--
781023	3.63 E2	8.90 E4	3.57 E3	1.59 E6	3.31 E5	54	38	5.28 E4
781027	3.93 E2	8.07 E4	3.78 E3	1.64 E6	3.36 E5	54	54	--
781030	4.12 E2	7.16 E4	4.30 E3	1.61 E6	3.39 E5	44	52	5.45 E4
781103	3.56 E2	6.97 E4	4.04 E3	1.61 E6	3.34 E5	46	53	--
781106	3.42 E2	6.36 E4	4.10 E3	1.52 E6	3.20 E5	41	49	4.77 E4
781113	3.19 E2	8.27 E4	4.56 E3	1.46 E6	3.23 E5	35	48	4.17 E4
781117	3.92 E2	5.98 E4	4.36 E3	1.43 E6	3.22 E5	≤38	78	--
781122	3.04 E2	5.91 E4	4.42 E3	1.33 E6	3.15 E5	44	89	4.02 E4
781127	2.86 E2	5.52 E4	4.78 E3	1.22 E6	3.13 E5	44	81	4.04 E4
781201	2.92 E2	4.80 E4	5.69 E3	1.12 E6	3.01 E5	43	89	--
781204	1.42 E2	3.09 E4	6.17 E3	1.06 E6	2.94 E5	≤32	61	4.02 E4
781208	97	2.49 E4	1.65 E5	8.83 E5	2.69 E5	≤27	42	--
781211	55	2.07 E4	1.15 E2	7.81 E5	2.43 E5	≤23	≤38	1.41 E3
781218	4.53 E2	5.74 E4	9.96 E2	6.81 E5	1.94 E5	≤36	59	1.51 E3
781227	3.85 E2	6.37 E4	9.65 E3	9.42 E5	1.74 E5	≤29	67	6.69 E2
790104	3.41 E2	6.35 E4	≤31	7.60 E5	8.90 E4	≤25	66	9.36 E2
790111	3.06 E2	6.06 E4	≤7	6.72 E5	4.67 E4	≤32	65	1.22 E3
790115	2.10 E2	7.75 E4	≤12	7.01 E5	5.08 E4	≤21	56	1.34 E3
790122	1.12 E2	7.30 E4	≤22	4.57 E5	3.18 E4	≤37	65	8.87 E2
790129	2.08 E2	7.45 E4	≤12	6.06 E5	3.58 E4	≤19	52	1.29 E3
790206	2.90 E2	8.23 E4	≤21	8.02 E5	2.94 E4	≤22	70	1.78 E3
790212	2.81 E2	8.09 E4	≤57	1.01 E6	5.10 E4	≤25	94	2.03 E3
790305	4.33 E2	7.54 E4	≤15	3.08 E4	2.02 E4	≤19	≤63	81
790313	5.31 E2	8.94 E4	≤24	5.56 E5	3.66 E4	≤28	≤45	≤64
790326	5.19 E2	1.01 E5	≤41	7.65 E5	3.83 E4	≤38	≤60	≤54
790409	5.58 E2	1.14 E5	1.08 E2	7.79 E5	4.61 E4	≤35	≤48	≤68
790423	4.29 E2	--	43	6.44 E5	4.19 E4	46	≤30	48
790507	5.20 E2	1.16 E5	7.98 E3	7.56 E5	6.87 E4	≤29	37	68
790521	1.02 E3	1.25 E5	2.51 E4	8.55 E5	7.83 E4	≤33	38	1.11 E2
790604	4.30 E2	1.79 E5	≤41	5.58 E5	2.59 E4	≤18	≤30	55
790619	5.34 E2	1.24 E5	2.83 E3	6.24 E5	3.33 E4	≤46	≤52	≤81
790702	8.68 E2	1.32 E5	1.64 E4	7.33 E5	5.01 E4	≤45	≤52	1.03 E2
790716	7.82 E2	1.58 E5	1.99 E4	6.79 E5	4.57 E4	≤21	≤34	2.27 E2
800527	1.37 E2	2.51 E4	2.82 E4	2.47 E5	1.35 E4	≤17	≤21	2.44 E2
810526	2.58 E2	3.61 E4	5.07 E3	1.52 E5	2.74 E5	≤12	≤24	9.48 E2
820524	≤60	8.70 E3	3.63 E4	1.07 E5	1.11 E4	≤60	≤60	66

APPENDIX 2. TRITIUM ANALYSES AT OAK RIDGE NATIONAL LABORATORY AND U.S. GEOLOGICAL SURVEY LABORATORIES FOR SAMPLES COLLECTED OCTOBER 16, 1978

[Results are given in disintegrations per minute per milliliter of sample (dpm/mL). E is exponent to the base 10]

Well number	ORNL laboratory	USGS laboratory[1]		Number of dilutions
		Count after distillation	Count without distillation	
4-4	65	69.6 ± 1.3	69.2 ± 1.3	0
4-5	3.21 E4	3.08 E4 ± .07 E4	3.24 E4 ± .07 E4	1
4-6	6.51 E5	6.88 E5 ± .16 E5	6.84 E5 ± .16 E5	2
4-7	7.53 E6	7.79 E6 ± .18 E6	7.80 E6 ± .18 E6	2
4-8	1.19 E6	1.83 E6 ± .04 E6	1.85 E6 ± .04 E6	2
4-9	1.12 E5	1.18 E5 ± .03 E5	1.19 E5 ± .03 E5	2
4-10	1.12 E3	1.14 E3 ± .03 E3	1.12 E3 ± .03 E3	1
6-4	3.32 E2	3.65 E2 ± .08 E2	3.60 E2 ± .08 E2	1
6-5	9.10 E4	8.81 E4 ± .21 E4	8.79 E4 ± .21 E4	2
6-6	3.03 E3	3.09 E3 ± .07 E3	3.03 E3 ± .06 E3	1
6-7	1.46 E6	1.59 E6 ± .04 E6	1.60 E6 ± .04 E6	2
6-8	3.05 E5	3.70 E5 ± .09 E5	3.57 E5 ± .09 E5	2
6-9	55	59.9 ± 1.1	60.5 ± 1.1	0
6-10	41	39.4 ± .8	39.0 ± .8	0
6-11	5.05 E4	4.77 E4 ± .12 E4	4.84 E4 ± .12 E4	2

[1]Most samples analyzed by the USGS were diluted in the laboratory to bring concentrations within the range of about 35 to 75 dpm/mL. All USGS samples were split. One part was counted after distillation and the other part was counted without distillation. The purpose of distillation was to remove higher energy emitters, if present.

APPENDIX 3. APPARENT HYDRAULIC CONDUCTIVITIES OF TEST WELLS

[Data are from Webster and Bradley (1988). Refer to pages 20 and 26 of that report for method of analysis and discussion of factors influencing data accuracy. E is exponent to the base 10]

Site near burial ground 4		Site in burial ground 6	
Well no.	Apparent hydraulic conductivity (feet per day)	Well no.	Apparent hydraulic conductivity (feet per day)
4-4	1.2 E-2	6-4	6.2
4-5	2.0 E-2	6-5	6.7
4-6	2.3 E-2	6-6	1.1
4-7	3.4 E-2	6-7	(a)
4-8	1.0 E-2	6-8	2.4
4-9	2.5 E-2	6-9	1.6
4-10	4.0 E-2	6-10	8.6 E-1
4-11	1.6 E-2	6-11	(b)

(a) Graph of water-level response as a function of time did not match type curve.
(b) Well contained insufficient column of water to conduct a test.